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Supply risks associated with CdTe and CIGS thin-film photovoltaics

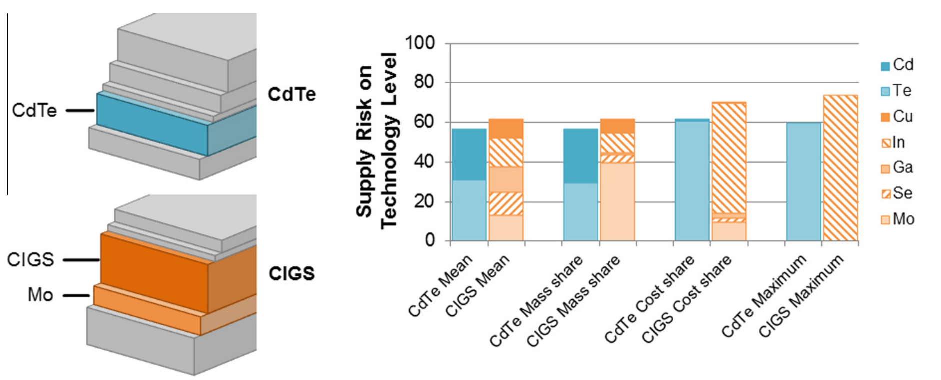
Christoph Helbig [a,*], Alex M. Bradshaw [b,c], Christoph Kolotzek [a], Andrea Thorenz [a], Axel Tuma [a]

[a] Resource Lab, University of Augsburg, Universitaetsstr. 16, 86159 Augsburg, Germany
[b] Max Planck Institute for Plasma Physics, Boltzmannstraße 2, 85748 Garching, Germany
[c] Fritz Haber Institute, Faradayweg 4-6, 14195 Berlin, Germany

HIGHLIGHTS

- Supply risks associated with thin film photovoltaic technologies are considered.
- Eleven supply risk indicators are used to evaluate Cd, Te, Cu, In, Ga, Se and Mo.
- Indicator weighting based on peer assessment and an Analytic Hierarchy Process.
- Various possibilities for the aggregation of elemental supply risks discussed.
- Aggregated results show a marginally lower supply risk for CdTe than for CIGS.

GRAPHICAL ABSTRACT



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ABSTRACT

As a result of the global warming potential of fossil fuels there has been a rapid growth in the installation of photovoltaic generating capacity in the last decade. While this market is dominated by crystalline silicon, thin-film photovoltaics are still expected to make a substantial contribution to global electricity supply in future, due both to lower production costs and to recent increases in conversion efficiency. At present, cadmium telluride (CdTe) and copper-indium-gallium diselenide ($CuIn_xGa_{1-x}Se_2$) seem to be the most promising materials and currently have a share of ≈9% of the photovoltaic market. An expected stronger market penetration by these thin-film technologies raises the question as to the supply risks associated with the constituent elements. Against this background, we report here a semi-quantitative, relative assessment of mid- to long-term supply risk associated with the elements Cd, Te, Cu, In, Ga, Se and Mo. In this approach, the supply risk is measured using 11 indicators in the four categories "Risk of Supply Reduction", "Risk of Demand Increase", "Concentration Risk" and "Political Risk". In a second step, the single indicator values, which are derived from publicly accessible databases, are weighted relative to each other specifically for the case of thin film photovoltaics. For this purpose, a survey among colleagues and an Analytic Hierarchy Process (AHP) approach are used, in order to obtain a relative, element-specific value for the supply risk. The aggregation of these elemental values (based on mass share, cost share, etc.) gives an overall value for each material. Both elemental and "technology material" supply risk scores are subject to an uncertainty analysis using Monte Carlo simulation. CdTe shows slightly lower supply risk values for all aggregation options.

* Corresponding author.
E-mail address: christoph.helbig@wiwi.uni-augsburg.de (C. Helbig).

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1. Introduction

The advantages of photovoltaic (PV) solar energy are direct electricity production, simple mechanical construction and, most importantly, a very substantial reduction in greenhouse gas emissions compared to fossil fuels [1–3]. As a result, there has recently been an astonishing growth in photovoltaic capacity worldwide, despite the serious problem of intermittency and the apparent reluctance to address the resulting storage challenges. In fact, the annual growth in globally installed photovoltaic capacity has been around 40% per annum in recent years, resulting in a cumulative total of 177 GWp in 2014 [4], corresponding to a contribution to global electricity supply (in terms of energy) of about 190 TW h, or 1% [5]. This strong market growth – aided in many countries by subsidies and generous feed-in tariffs – has been accompanied by substantial price decreases in recent years. The market for photovoltaic modules is currently dominated by crystalline silicon technology, in the form of single crystal or polycrystalline wafers. Although the market share of thin-film photovoltaics, consisting mainly of cadmium telluride (CdTe) and copper-indium-gallium diselenide, or CIGS ($CuIn_xGa_{1-x}Se_2$) has recently fallen, there is reason to believe (Section 2) that these technologies will soon be able to position themselves more strongly in the market.

If thin-film photovoltaics were indeed to make a substantial contribution to global electricity supply later in this century, and – a second assumption – if CdTe and CIGS modules were to dominate this market, then the question arises as to the mid- to long-term supply risks associated with the constituent elements of these two materials. Supply risks describe the possible lack of availability of minerals and elements; they can be assessed, at least in a qualitative or semi-quantitative way. For elements, for which it is perceived that there could be a supply risk problem in coming years, the term "critical" is often used [6–9]. The debate concerning the availability of minerals and their constituent elements has been going on for over half a century [10–14]. Initially, it focused on the (limited) quantities contained in the mineral deposits of the Earth's crust and was driven by the fear that there would not be sufficient amounts to cover the requirements of a technologically advanced society with a growing population. Thus, Goeller and Weinberg, for example, warned about the impending mineral depletion problem and how it could perhaps be overcome through recycling and substitution (and a considerable amount of energy!) [11]. They were contradicted in a vigorous rebuttal by Simon, a well-known "cornucopian" [12]. The last two decades have actually seen a massive increase in the use of many "rare" metals for a variety of new, high-tech applications. (The term "rare" is often used when the elemental concentration in the continental crust is lower than about 0.1% [15].) This in turn has led to considerable interest in supply risk assessments [7,16–23]. As noted above, early studies concentrated on the possibility of a serious depletion of mineral stocks in the Earth's crust. There are usually two "indicators" in such assessments that are associated with the extent of the known reserves as well as with the known and putative resources of a particular element. In recent years, further indicators have been formulated to account for the many other factors that can contribute to the supply risk. Extraction as a by-product during the mining of another metal is, for example, a further supply risk, since availability depends on the technology and profitability of extraction of the "parent" metal [24]. Many by-product metals are also rare and/or characterized by a lack of economically viable deposits; they often lack recycling potential, which is another supply risk aspect [25,26]. Other indicators cover factors such as concentration risk when supply is in the hands of only a few companies and/or countries, possible future demand for other technological applications, and political risks such as instability and governance standards in producing countries. From the numerous studies of supply risk for raw materials published in the last ten years Achzet and Helbig [19] have recently identified as many as 20 indicators used by various authors.

How can supply risks be assessed using such indicators? A study published by the EU Commission is perhaps a good example [7]. It uses a so-called risk assessment matrix, based on the two composite indicators "supply risk" (consisting of various different supply risk indicators) and "economic importance", and sets threshold values for each. Materials exceeding both of these values are designated as being critical. Forty-one non-fuel metals and minerals were investigated, of which 14 were designated as critical. In a second study [27] some years later using the same indicators and, most importantly, the same thresholds, the list was modified. Several recent studies have been concerned specifically with energy-related materials, i.e. materials that are required for the generation, transmission, storage and utilization of energy, in particular those that will be needed for the transformation to a low-carbon energy economy [20,21,28–40].

Several authors have recently considered thin-film CdTe and CIGS photovoltaics from the point of view of technological relevance [3], environmental impacts [41], demand- and supply-side economics or costs [42–47], and materials supply risk [20,48–53]. Graedel and Nuss [50] have made a multi-element, multi-indicator study of supply risk for CdTe and CIGS absorber materials based on their extensive "criticality" data bank of the elements [18,54,55]. Goe and Gaustad [20] have also studied photovoltaic materials using mainly U.S.-based data and several indicators but, like Graedel and Nuss, do not broach the problem of aggregation, i.e. the determination of the relative supply risks associated with the two compounds. In the present paper, we first determine the supply risk associated with the two elements, Cd and Te, as well as the supply risk associated with the five elements Cu, In, Ga, Se and Mo. Our philosophy is, however, somewhat different than that of the two previous papers, in that our eleven indicators are chosen and categorized (as in a previous study of some of the authors [56]) and weighted (using a questionnaire answered by colleagues in both academia and industry) for the specific case of thin film photovoltaics. Moreover, in order to assess relative supply risks for the two compounds, various aggregation procedures for the supply risks associated with the individual elements, are explored and tested. While acknowledging the importance of environmental and sustainability factors, we emphasize that our composite indicators are intentionally based on supply risk only. Despite these differences in methodology, the present investigation can be seen as a further development of the Graedel and Nuss approach. We demonstrate not only the importance of a multi-indicator analysis that is as comprehensive as possible, but also of a product-oriented weighting of the indicators. Moreover, we show that the concept of supply risk on a comparative basis can be applied at the product, or technology, level, if thought is given to the aggregation problem.

The structure of the paper is as follows. In the next section we briefly describe the CdTe and CIGS technologies and report latest module efficiency data. Section 3 describes the supply risk evaluation model in detail. Section 4 shows the application of the technique first on the level of the elements themselves and then for the two technologies. The article concludes (Section 5) with a discussion and a summary.

2. Thin-film photovoltaics

By way of illustration, typical CdTe and CIGS solar cells are shown schematically in cross-section in Fig. 1 (after Refs. [32,57]). Note that only those (functional) layers are shown which