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Identifying critical materials for photovoltaics in the US: A multi-metric approach

Michele Goe, Gabrielle Gaustad *

Golisano Institute for Sustainability, Rochester Institute of Technology, 111 Lomb Memorial Drive, Rochester, NY 14623, United States

HIGHLIGHTS

- Ever increasing non-fuel material consumption has heightened energy security concerns.
- Sustainability related metrics enable policymakers a more comprehensive approach.
- Single score and metric aggregation oversimplify or confound indicator trends.

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ABSTRACT

There are increasing concerns that physical material constraints threaten energy security and the growth of emerging technologies. Traditional approaches to quantify material criticality utilize single-score metrics which are narrowly focused on physical scarcity and often lead to command-and-control policies. However, a broader definition of criticality that goes beyond physical scarcity to include sustainability metrics e.g. embodied energy, political instability, economic value can provide policymakers with a more comprehensive perspective of the complex and highly interconnected relationships between indicators. We use the case of solar photovoltaic materials to demonstrate the challenges and opportunities in critical materials policy and indicator choices. For silicon-based and thin-film photovoltaics in particular, Ge, Pt, As, In, Sn and Ag were found to be the most critical relative to the 17 materials studied. Multi-metric analysis for these materials reveals tradeoffs that suggest friction between sustainable economics, political stability of supply, and environmental quality objectives.

1. Introduction

The United States is a dominant consumer of primary energy and materials in the world. However, the growth of emerging economies such as China and India and their increasing consumption of energy and materials have begun to draw attention towards materials availability and criticality concerns. Further deepening these concerns is the recognition of the United States' import reliance on primary energy fuels and some primary materials; of particular relevance are rare earth metals with applications in emerging electrical and energy technologies that are mined in adversarial or socio-politically unstable nations [1]. One emerging technology that may be essential to US energy security and climate change mitigation is solar photovoltaics (PV). With respect to life cycle carbon emissions and land use, PV technologies have less environmental impact than traditional energy technologies i.e. coal power plants [2,3]. This implies that broad PV deployment would significantly reduce global greenhouse gas emissions and its associated climate impacts. However, it has been suggested that material availability is a potential constraint for broad deployment of PV [4–7]. For example, current silicon-based and thin-film solar PV's core technology depends on several primary materials i.e. In and Te which were recently determined to be of high importance for the development of a clean energy economy and at near-critical or critical supply risk by the U.S. Department of Energy (DOE) [8]. Recent PV research also assesses the broader impacts of critical and non-critical material choice [9–14].

Concerns over material availability, especially for emerging technologies, are not new and over the last 70 years have sparked debates as well as national policies aimed at securing critical materials [15]. These policies continue to be implemented despite the lack of a broader definition of criticality. For example, the most recent Department of Defense (DoD) Strategic and Critical Materials report per the Strategic and Critical Materials Stockpiling Act [16] uses material consumption, production, and projected future demand to determine the severity of material criticality. Similarly, in previous literature [4,17–20], the material availability is

* Corresponding author. Tel.: +1 585 475 6089.
E-mail address: gabrielle.gaustad@rit.edu (G. Gaustad).

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determined primarily by physical scarcity, however, systems level considerations such as the production share of politically instable nations, toxicity, embodied energy, or the value to the economy are not considered. The use of a broader definition of criticality would likely increase the scope to include energy intensive materials such as aluminum and silicon that are not physically scarce but have broad economic and environmental implications.

1.1. Aims of this study

Earlier literature claimed material criticality concerns at the policy level were waning by pointing to increased foreign mineral reliance and decreased domestic mining [21–23]. Similar circumstances have motivated recent interest in identifying critical materials. Several nations including those in the European Union (EU) have recently identified materials that are common to photovoltaics (e.g. In, Ga, and Ge) as critical in terms of supply risk and economic importance [24–28]. However these studies lack sensitivity of results to data uncertainty and organization; they also rely on relative rather than normative determinations of criticality which lack context for (future) supply risks. For example, the Centre for Policy Related Statistics' aggregation of product groups masks supply chain dependencies. The Morley et al. study contains no clear environmental metric and aggregates similar metrics (e.g. depletion time, reserve base) to determine a single criticality "score" which ignores the interdependence of data. Other criticality studies have proposed methodology to ascertain the supply risk from a corporate, national, and/or global perspective [29,30]. Furthermore, none of the studies mentioned above address uncertainty as to the impact of a limited supply of base metals such as Cu, Al, or Zn on the criticality of their by-product metals (e.g. Te for Cu, Ga for Al, and In for Zn). Lastly, these studies are limited in the breath of criticality metrics especially with regards to economic and environmental risks which would provide policymakers with a more systemic perspective.

Several questions arise from the afore mentioned literature gaps: What metrics are useful for policy-makers in assessing and regulating criticality issues? What policies would address metal criticality while at the same time continue to encourage solar PV adoption?

Addressing criticality in policy is challenging due to the complex, highly interconnected geopolitical relationships of supply chains, infrastructure lock-in, and increasing material demand that must be balanced with low carbon supply. This work aims to quantify and compare a uniquely broad set of criticality metrics for silicon-based and thin-film i.e. cadmium telluride (CdTe), copper indium diselenide (CIGS), amorphous silicon (a-Si) PV technologies that focus on a more comprehensive or life cycle systems approach which is unique in its inclusion of environmental metrics. This analysis highlights comparisons between metrics and combinations of metrics. In addition, we suggest how to depart from traditional command-and-control policies utilizing the aforementioned metrics to mitigate criticality in the short and long term.

1.2. Criticality definition and materials considered

Material criticality, as defined here, is a relative concept in that it compares materials against each other to determine which materials have the greatest risks of disruption to supply. In this analysis, the focus is on PV materials and also includes impacts on the economy and the environment. In order to evaluate the criticality of solar PV materials from the perspective of the US. we characterize three areas of criticality: supply risk (Section 3.1), economic risk, (Section 3.2) and environmental risk (Section 3.3). This is a semi-dynamic study in that we include select data for materials over a 20-year period (1992–2012) commenting on their trends in the context of the decision making for policy. The solar PV materials considered in this study and their previously identified criticality issues are summarized in Table 1.

2. Methodology

In order to evaluate example risks to supply, the environment, and the economy, several criticality components were selected for these broad criticality risk groups. Many indicators or metrics exist for any of these components; the selection of the indicators listed in Table 2 was motivated by broad applicability to the PV materials of interest and data availability. A key challenge in assessing criticality is to synthesize and appropriately weigh indicators of various scales and units. Previous studies have aggregated and weighed multiple indicators based on national priority or arbitrarily [8,33]. For a clear comparison, this work uses percentages or normalization to characterize the various criticality indicators. Many of the calculated metrics are universal in nature such as embodied energy, material reserve bases, or political stability, however, this particular analysis often takes a United States based approach, for example using national primary prices, using the US as the denominator for calculating import reliance, and using toxicity scores developed by the U.S. Environmental Protection Agency

Table 1
Potential critical solar PV metals considered for this study.

Material	Previously identified criticality issues	Source
Aluminum (Al)	Economic importance	[24,31]
	Defense/Military importance	
Arsenic (As)	Toxicity	[30]
	High import reliance	
Cadmium (Cd)	Toxicity	
Copper (Cu)	Defense/Military importance	[31]
Iron (Fe)	Global demand	[27]
Gallium (Ga)	Low substitutability	[24,28,32]
	Recycling constraints	[8,27]
	Producer trade restrictions	
	Import reliance	
	Importance to "clean energy"	
	Carbon footprint of mining and production	
Germanium (Ge)	Economic importance and supply risk	[24,32]
	Substitutability	[27]
	Carbon footprint of mining and production	
Gold (Au)	Carbon footprint of mining and production	
Indium (In)	High demand from emerging technologies	[24]
	Technical difficulty of recycling and substitution	[28,32]
	Import reliance	[8]
	Secondary production constrained	
	Importance to "clean energy"	
	Geological scarcity	
Molybdenum (Mo)	Economic importance	[24]
	Limited number of mining corporations	
	Substitutability	
Platinum (Pt)	Regional concentration of mining	[32]
	Recycling restriction	
	Rapid demand growth	
Selenium (Se)	Net import reliance	[24]
Silicon (Si)	Recycling constrained	[27]
	Global demand	
Silver (Ag)	Toxicity	[27]
	Political instability of producers	
	Climate change vulnerability of producers	
Tellurium (Te)	Economic importance	[24]
	Recycling constraints	[8,32]
	Importance to "clean energy"	[27]
	Geological scarcity	
Tin (Sn)	Substitutability, political instability of producers	[27]
Zinc (Zn)	Economic importance	[24,31]
	Defense/Military importance	[27]
	Political instability of producers	