Primary and Secondary Material Flows for the Future Global Deployment of Silicon-based Photovoltaic Systems

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Executive Summary

The anticipated expansion in PV installed capacity will increase demand for raw materials necessary for manufacturing and deployment. This aligns with global decarbonization scenarios and recent research which identify rapid expansion of renewable energy capacity as “the single largest driver” of near-term emissions reductions on pathways to net-zero by 2050 [1]. Silicon-based PV dominates global production (~98%), consequently this report focuses on Silicon based PV [2], [3], [4]. Nevertheless, a number of silicon-based PV materials are classified as “critical” in several major economies based on region-specific assessments of potential supply disruptions and economic importance [5]. Recent estimates suggest that annual PV demand could peak at approximately 40% of global silicon production, 44% of silver, 25% of copper [6], which poses potential constraints to large-scale PV deployment. Despite growing attention to this topic in the literature, there are two clear gaps in understanding: (1) evaluating raw material demand at the system level with respect to ongoing technological shifts, and (2) accounting for dynamic reductions in material intensity that are already reshaping the scale of future demand.

This report presents a dynamic material flow analysis (dMFA) model for estimating future silicon-based PV system-related raw material demand, secondary supply, and in-use stock, with deployment scenarios ranging from 29 TWp to 75 TWp of installed global silicon-based PV capacity by 2050. In this report, ‘secondary supply’ refers to the material content of modeled EoL PV outflows under the assumed collection and recovery conditions. Unless otherwise specified, these estimates represent theoretical availability in the waste stream and do not imply that the material can be fully recovered, purified to PV-grade specifications, or reintegrated into PV manufacturing. The model assumes that future PV deployment will continue to be dominated by silicon-PV. Within that, it accounts for expected shifts in the future market share of including aluminum back surface field (Al-BSF), mainly for sales prior to 2025, as well as passivated emitter and rear contact (PERC), tunnel oxide passivated contact (TOPCon), silicon heterojunction (SHJ), interdigitated back contact (IBC), and perovskite-silicon-based tandem (Pvk-Si-tandem) technologies. Moreover, the model accounts for reductions in material intensity as manufacturing processes become more efficient, performance parameters improve, and materials are substituted or phased out. The analysis focuses on nine key elements: aluminum, copper, indium, lead, silicon, silver, gold, tin, and zinc. Results for other PV materials are aggregated at the component level.

The cell level is modeled based on the silicon wafer and the additional functional layers common to commercial cells, while the module level includes front and back glass, copper cell interconnections, as well as an aluminum frame. At the system level, a simplified bill of materials is applied for balance-of-system components to represent average material requirements per installed capacity, without distinguishing between different inverter configurations or cable layouts. System components excluded from the analysis, including foundations, floating structures, control systems, and battery storage, are discussed further in the limitations section. This study assumed full collection and 100% recycling efficiency for the future waste stream generated to provide a theoretical upper-bound estimate of total recycled material mass from retired PV systems. A sensitivity analysis is performed to determine the impact of uncertain future deployment scale and other technological factors on the silicon-based PV sector demand for key materials. Finally, the projected material demands of the global silicon-based PV sector are then evaluated in terms of resource depletion using the Abiotic Depletion Potential, ultimate reserves (ADP_{UR}) method, economic scarcity using the Abiotic Depletion Potential, economic reserves (ADP_{ER}) method, resource quality with the Surplus Ore Potential, Ultimate Recoverable Resources (SOP_{URR}) method, and resource criticality with the Integrated Method to Assess Resource-Use Efficiency (ESSENZ) method.

According to the dMFA model results, the global silicon-based PV sector is projected to consume between 145 and 280 million metric tons of copper cumulatively between 2025 to 2050, depending on the scale of future deployment. This demand is primarily driven by cables (75w%) and inverter (13w%) components. For aluminum, the cumulative demand from 2025 to 2050 is projected to range from 510 to 1 100 million metric tons. Mounting structures account for around 70w% of demand on average, with their share increasing from 66w% in 2025 to 72w% by 2050. The share of aluminum demand due to module frames is expected to decline from 29% to 23% between 2025 and 2050 due to the gradual adoption of frameless module designs. For silicon, cumulative 2025-2050 demand is projected to range from 60 to 120 million metric tons of solar-grade silicon, with more than 20% of the input silicon lost during wafer slicing. For silver, the cumulative 2025-2050 demand is expected to range between 100 000 and 200 000 metric tons, strongly dependent on the future market share of copper metallization and silver paste loading. The cumulative 2025-2050 indium demand is expected to range between 60 000 and 160 000 metric tons, strongly dependent on the future market share of ITO-based technologies. Tin demand comes primarily from solder alloys, with a minor contribution from ITO layers, and may range from 1-3 million metric tons.

The results show that copper is the PV material with potentially the biggest bottleneck in primary supply for future sector demand. Copper demand by the PV sector will peak in the mid-2040s at 7-15 million tons per year, equivalent to 30w%-65w% of the current annual global mine production [7]. Previous studies show that not all countries prioritize mine capacity expansion, and despite copper mining capacity growing at a 3% CAGR, a supply gap of 10.5-11.5 million metric tons is projected by 2035 [8], [9]. Peak annual demand for solar-grade silicon may range between 3 and 6 million metric tons by 2040, against current global capacity of about 3 million metric tons [10]. However, continued overcapacity in China and capacity additions from project pipelines suggest that supply constraints may be less severe [11], [12]. For silver, 2025-2050 cumulative demand represents roughly 15w%-30w% of current global reserve estimate [7], while annual use in PV cells is expected to peak at 9 000 metric tons, even in high-deployment scenarios. This is only a slight increase over the 8 600 metric tons estimated for 2024 shipments [13]. Tin cumulative demand between 2025 and 2050 could amount to 30w%-64w% of the estimated global Sn reserves reported for 2024 [7], depending on the deployment scenario. For all deployment scenarios, cumulative 2025-2050 indium demand is projected to surpass the most recent global reserve and resource estimate of 50

000 metric tons (2009 data [14], due to lack of a more recent authoritative estimate) by the mid-2040s. Nonetheless, reserve estimates and mine production figures evolve over time, and comparisons with future demand should be interpreted accordingly. Based on the latest figures replacement of indium in transparent conductive oxides (TCOs) is necessary for PV deployment at terawatt per year scale. Furthermore, alternative TCO materials are being tested, but they remain at a low technology readiness level due to varying stability, performance, and cost profiles [15], [16], which may limit their market penetration and contribution to reductions to future indium demand. Continued development of replacement material(s) for indium in TCOs, or reduction in quantity used per module, will be important for the indium consuming parts of the PV industry.

From 2025 to 2050, the mass of materials considered herein from decommissioned PV systems is expected to equal 15-20% of the total demand for those same materials over that period. This limited potential for closed-loop recycling is partly attributed to long product lifetime, which delays the availability of recyclable material, in addition to the purity of recovered materials [17]. However, exceptions for this trend are indium and silver. For indium, the relatively late commercialization and the expected large future market share of ITO-based technologies indicate that more than 90% of cumulative demand will remain in in-use stock by 2050, with the waste stream contributing only the remainder. Total silver mass in future silicon-based PV waste may supply 30-45w% of the cumulative demand between 2025 and 2050.

Based on the projected cumulative raw material demands during the timeframe of this study, the ADP_{UR} method identifies gold used in inverters as the largest contributor to resource depletion impacts (56%), followed by copper (33%) used mostly in cables, and silver (9%) used in cells. Hypothetically, 100% closed-loop recycling could reduce ADP_{UR} impacts by 25% and 17% under low and high deployment scenarios, respectively. The ESSENZ method identifies indium as the main driver of criticality impacts (75%) due to limited reserves and concentration of global refining capacity, followed by tin (9%) and silver (6%). Hypothetical 100% closed-loop recycling may potentially reduce overall criticality impacts by 10% at most, while increasing the relative contribution of indium to the ESSENZ score to 79% as its total mass in future silicon-based PV waste does not match the rapidly growing demand.

The material constraints identified in this study are presented at a time of rapid market expansion. Global PV module prices reached historic lows in 2024-2025 [18], which accelerated deployment beyond earlier International Energy Agency and BloombergNEF forecasts [19]. Meanwhile, the EU Critical Raw Materials Act [20], the US Inflation Reduction Act [21], and India's Production Linked Incentive scheme for solar manufacturing [22], together with ongoing trade tensions, are shaping manufacturing investment decisions and influencing where PV manufacturing capacity will be built over the coming decade [23]. Nevertheless, the findings of this study indicate that material efficiency improvements and material substitution strategies should be considered alongside incentives for domestic production and processing when designing policies to support PV deployment.