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Resource scarcity challenges of photovoltaics in Europe 2050

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This article examines the challenges confronting the EU in expanding the use of photovoltaics to satisfy its electricity demand, while concurrently addressing concerns relating to the materials involved. The study employs Life Cycle Assessment (LCA), particularly the impact category Abiotic Resource Depletion (AD), on a range of scenarios of the deployment of photovoltaics (PV). Two principal scenarios for the year 2050 are considered: a baseline scenario reflecting current trajectories with higher shares of mono- and multi-crystalline silicon (c-Si) and a high thin-film scenario with an increased market share for thin-film technologies. The findings underscore the pivotal role of material constraints, particularly those about tellurium, silver, and gold, in both scenarios. The results demonstrate that in the baseline scenario with a higher share of c-Si technology, the highest AD values show gold, tellurium, and silver. Higher thin-film shares of PV result in a slight increase in tellurium demand while reducing the requirements for gold and silver. These high AD values indicate potential supply risks of the extraction and processing of these materials. The results also emphasize the necessity for technological innovation, improved recycling, and diversified supply chains to achieve sustainable PV growth in Europe.

1 Introduction

International bodies such as the International Energy Agency and the Intergovernmental Panel on Climate Change have long acknowledged the pivotal role of photovoltaic (PV) technology in limiting global warming.[1] The PV market has demonstrated a striking expansion over the past few decades, with the cumulative installed capacity worldwide exceeding 1.58 TWp by 2024.[2] Global projections suggest that about 75 TWp or more of deployed PV will be needed by 2050 to meet decarbonization goals.[3] In the EU, 253 GWp are installed, and by 2050, Europe has set itself the objective of significantly scaling up its PV capacity.[4,5]

More conservative prediction scenarios estimate PV capacity around 592 GWp for 2030, reflecting lower targets based on REPowerEU.[5] International Renewable Energy Agency (IRENA) predicts at least 891 GWp for 2030.[6] By 2050 the Joint Research Centre (JRC) ProRes scenario estimates total PV capacity of 2078 GWp, and the Zero Carbon scenario expects 3006 GWp.[7] The energy system model for Europe from Jülich Systems Analysis – ETHOS Europe – indicates 2921 GWp of PV in 2050.[8] Based on these numbers, it can be inferred that the EU's market share of PV will be significant. Given the projected dominance of PV in the electricity mix and the expected growth trajectory, it is reasonable to estimate that the PV capacity in the EU will exceed 1000–3000 GWp by 2050 (see Fig. 1).

The majority of PV installations use crystalline silicon (c-Si) modules, which currently account for more than 97% of overall cell production.[9] Silicon (Si), silver (Ag), and aluminium (Al) are the leading materials in c-Si panels.[9] Emerging technologies like thin-film solar cells and perovskite-based solar cells make up most of the remaining market and show promise for further innovation and diversification in the PV landscape. Perovskite solar cells have low cell stability; this issue still must be solved, and their contribution in the future is uncertain.[10] This similarly applies to thin-film technologies, such as cadmium telluride (CdTe) and copper indium selenide (CIS). However, they offer enhanced flexibility and reduced production costs, since they are much thinner and less material-intensive.[11,12]

Ambitious goals of large-scale PV deployment present a number of challenges, particularly from a material perspective. Existing work on material depletion due to PV can broadly be grouped into two strands. The first strand uses material flow analyses (MFA) to quantify future metal demand for PV deployment and to compare this demand with known reserves and resources. MFA models PV modules, emphasizes annual dynamics in PV deployment capacity, derives maximum deployable capacities for different PV technologies, and highlights elements such as indium, tellurium, silver, and gallium as potential constraints under high-growth scenarios.[13,14] The goal of MFA is to evaluate material demand, analyse improvements in material intensity, and PV technology choices.

A second strand relies on Life Cycle Assessment (LCA), translating emissions and resource demand into environmental impacts. LCA-based studies evaluate abiotic resource depletion

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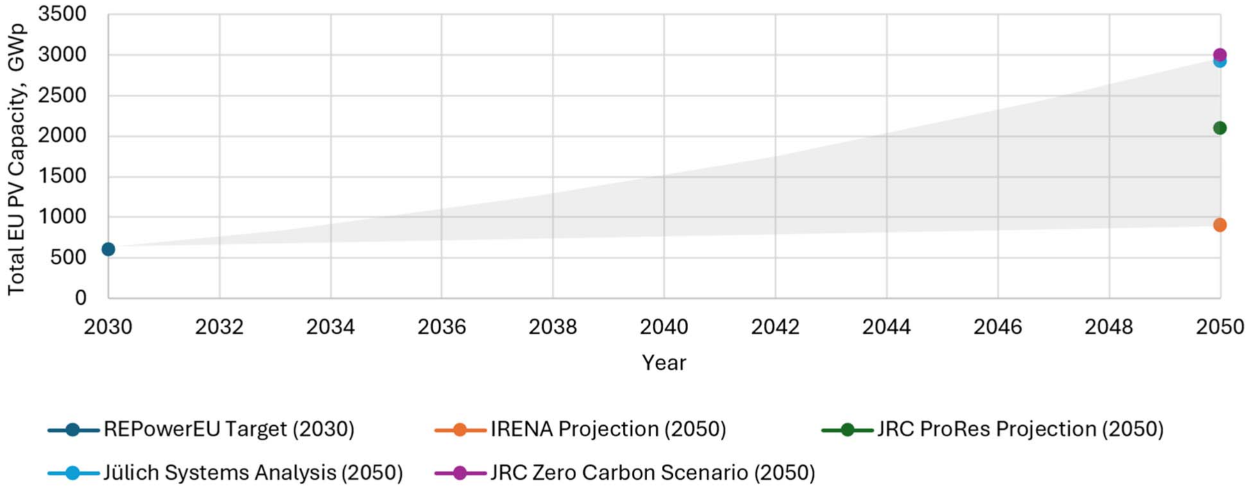

Fig. 1 PV Outlook – corridor of cumulative installed capacities in EU for 2030 and 2050 predictions.[4–8]

(AD) to characterize resource use. AD impact category, based on CML, states how quickly a resource is being consumed relative to geological reserves.[15] An LCA approach compared to MFA enables consistent comparison of AD impacts of different PV technology mixes and integration of other environmental impact categories into the analysis. LCA tracks the whole life cycle of PV, including background systems, providing a holistic and comparable depletion metric. Background systems comprise all upstream and auxiliary processes that enable PV deployment: mining and refining of metals, production of glass, polymers, and chemicals, balance of system components (inverters, mounting structures, cabling), and even background electricity mixes used in manufacturing.

A small number of PV LCA studies have made AD impact a central focus of the LCA. Among them, the IEA PVPS Task 12 report "Mineral Resource Use Footprints of Residential PV Systems" explicitly evaluates PV systems using multiple AD approaches. The results demonstrated high contributions of gold, silver, copper, tellurium, and cadmium, which made up to 98% of total resource depletion impacts.[16] Another study by Zhang *et al.* (2021) modelled multi-terawatt manufacturing scenarios and demonstrated essentially high AD results due to the use of silver and indium.[17] Abiotic depletion of caesium on the example of perovskite was analysed by Vidal *et al.* (2020).[18] Although existing studies provide valuable insights using the AD assessment method, no study has systematically projected the long-term material implications across technology deployment scenarios for Europe for the year 2050.

In this study, we analyse several PV deployment scenarios for Europe in 2050 using static LCAs and compare them to a reference LCA for the year 2024. Throughout the paper, we address two related but distinct questions: (i) how PV deployment scenarios affect global geological depletion of key metals, as captured by AD, and (ii) how this physical depletion interacts with Europe's structural import dependence and limited domestic mining capacity. In this study, we use 'resource scarcity' to describe the relative depletion of non-renewable geological reserves, as quantified by AD impact in LCA. We then discuss how this physical scarcity interacts with geopolitical dimensions of supply risk, such as the concentration of production. The paper is structured as follows: in Section 1, the current state of PV technologies is reviewed; in Section 2, the AD method and study design are described; in Section 3, the results are presented, and in Section 4, they are discussed. In Section 5, a conclusion is provided.

2 Methodology

2.1 Life cycle assessment and abiotic depletion

LCA is a standardized method to quantify the environmental impacts of a product or system over its entire life, from raw material extraction to end of life. LCA methodology in this study was employed following ISO 14040 and 14044 standards. The LCA is conducted using Sphera's software LCA for experts and the ecoinvent database version 3.10 cut-off.[19] In practice, LCA works in four main steps. The environmental impacts are assessed using the implemented AD impact assessment method.[20] AD represents an impact category concerned with the potential depletion of non-living, non-renewable resources (metals, minerals, and fossil energy carriers). In the life cycle impact assessment (LCIA) phase, inventory flows are multiplied by AD characterization factors. These factors are derived from a mathematical framework that employs a ratio where the annual extraction volume (E) of a given resource i is proportioned against its ultimate reserve estimate (R). To normalize for varying stock magnitudes across different resources, this extraction-to-reserve ratio is further divided by the reference reserve estimate itself.[15] Results are expressed in antimony equivalent units (kg Sb-eq), providing a standardized metric for comparative analysis. This indicator framework is designed to address the fundamental question: "What is the relative magnitude of a product system's contribution to global resource depletion patterns?" A higher AD value indicates that a product system contributes more strongly to the global depletion of a given resource, relative to antimony, and that in our context, this is interpreted as a higher contribution to long-term geological scarcity. AD factors are periodically updated when their underlying reserve and extraction data are revised, or when methodological changes are made.[20]

$$\mathrm{ADP}_i = \mathrm{CF}_i = \frac{E_i/R_i}{E_{\mathrm{red}}/R_{\mathrm{ref}}} \times \frac{\frac{1}{R_i}}{\frac{1}{R_{\mathrm{ref}}}} = \frac{E_i/{R_i}^2}{E_{\mathrm{ref}}/{R_{\mathrm{ref}}}^2}$$

2.2 Study design and functional unit

For the analysis, PV deployment and technology mix assumptions are to be made to define the FU of the LCA. Fig. 2 visualizes the annual installations of PV, reflecting possible future deployment rates, incl. annual replacement. Replacements were assumed based on a lifetime expectancy of PV systems of 25 years, where at least 80% of performance warranty is guaranteed.[21,22] We assumed this lifetime for all components, incl. inverters and mounting systems. Replacements were calculated based on the PV installations in the years 2005–2025, see Fig. 2. Thus, based on a uniform lifetime of 25 years, all installations of the year 2025 have to be replaced in the year 2050. New capacity additions are derived from the difference between the projected 2050 capacity (based on 3000 GWp in the Zero Carbon scenario) and the 2030 REPowerEU target of 600 GWp, with the assumed linear growth of the annual installations. Together, these values define the annual installation rates required to achieve the projected target of 3000 GWp. The FU is thus defined as 240 GWp installed PV in the year 2050. Several possible PV technology shares are differentiated in two scenarios. Thin-film expansion remains more uncertain;[23] thus, a separate scenario is added to explore a higher market share for thin-film technologies.

2.2.1 Baseline scenario 2050. In this scenario, c-Si modules are expected to continue to dominate the solar PV market. A 90% market share for c-Si and 10% share for thin-film technology is assumed. We emphasize that this share is a modelling assumption for scenario analysis rather than a forecast derived from a specific energy-system scenario. For simplification reasons, a 50/50 split between multi- and mono-c-Si was assumed for c-Si and a 50/50 split between CdTe and CIS was assumed for thin-film market shares.

2.2.2 High thin-film scenario 2050. In this scenario, c-Si modules are expected to continue to dominate the solar PV market, and thin-film achieves a higher market share of 30% by 2050 (50/50 split). 70% of PV is c-Si with a 50/50 split between multi- and mono-c-Si. For this scenario, we clarify that the thin-film share is chosen as an exploratory upper bound, deliberately exaggerating its uptake to test its impact on resource depletion.

As a reference for the results of the 2050 scenarios, an LCA of the year 2024 is performed. 65.5 GWp of PV were installed in the EU in 2024, which was taken as FU. The PV market was dominated by c-Si technology, which accounted for approximately 95% of total installations, while thin-film technologies comprised the remaining market share.[5] Again, an even split between thin-film technologies was assumed. Fig. 1 and 2 provide context for the assumed 2050 capacity and annual installation rates, but the LCA results themselves are calculated for discrete years. 2030 appears only as an intermediate capacity target used to calculate annual additions, but no LCA was carried out for 2030.

2.3 Life cycle inventories

LCA examines supply chains of PV. LCI data were used based on commercial PV modules (multi-silicon, mono-crystalline

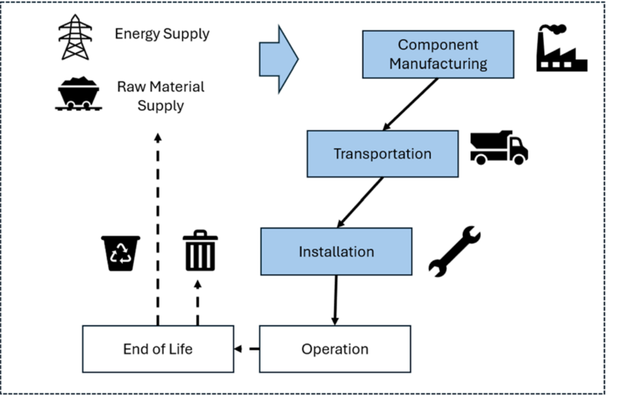

Fig. 3 System boundaries of this study. Blue boxes are included in the LCA; white boxes are excluded.

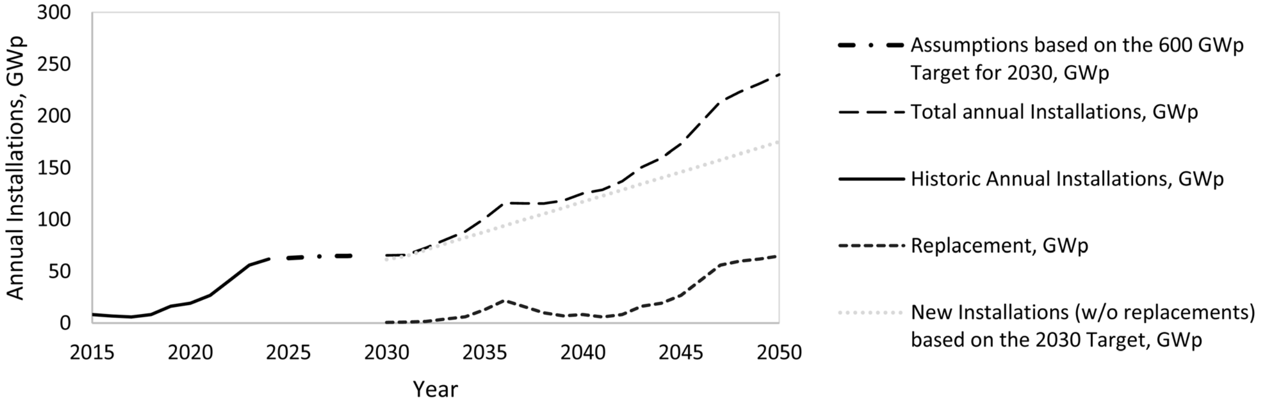

Fig. 2 Annual PV installations in the EU based on own calculations and projected cumulative capacity targets (the 2030 REPowerEU target of 600 GWp and 3000 GWp in the Zero Carbon scenario 2050).[25–28]

silicon, thin-film CdTe, thin-film CIS) of Task 12 PV Sustainability – Methodology Guidelines on Life Cycle Assessment of Photovoltaic.[24] PV installations of modules, inverters, trackers, mounting structures, and general electrical components were modelled (see Fig. 3). Operation and End of Life of the modules are not modelled, since they are not relevant for the FU impact, and the electricity output was not the goal of this LCA. Substantial reductions in key materials can also be expected for the next few decades.

This reduction can be modelled using learning rates, which reflect how much material usage decreases with each doubling of cumulative production. Hallam *et al.* (2022)[25] claim a learning rate of 20% for PV, which is also used in other literature and in the model.[14,26] Going from 60 GWp to 240 GWp is a factor of 4, *i.e.*, two doublings. Additionally, simplified recycling is considered. It is implemented as a cut on primary flows, reducing the primary material demand of all flows by 10%.[27] Thus, no separate AD factors are defined for recycled materials.

3 Results

This chapter presents AD results for EU PV deployment scenarios: one for the year 2024 and two scenarios for the year 2050. Section 3.1 examines the baseline c-Si-dominated scenario, Section 3.2 analyses the thin-film (CdTe/CIS) scenario, and Section 3.3 compares 2024 baseline *vs.* 2050 projections. All AD impacts are shown in antimony equivalents (t Sb-eq).

3.1 Results of the baseline scenario 2050

The analysis highlights significant challenges associated with the depletion of PV materials, particularly gold, tellurium, and silver. Fig. 4 displays the AD impacts for 12 materials in the baseline scenario of 2050. Three materials dominate the resource depletion profile: gold, tellurium, and silver, collectively accounting for over 80% of total AD impact. All remaining materials show substantially lower AD impacts, with most falling below 250 t Sb-eq, highlighting the disproportionate AD impact of the top three materials. Fig. 4 shows an increase across all materials compared to 2024, with gold reaching 5010 t Sb-eq compared to 1396 t Sb-eq in 2024, tellurium 4,821 t Sb-eq compared to 1240 t Sb-eq, and silver 4226 t Sb-eq compared to 1203 t Sb-eq.

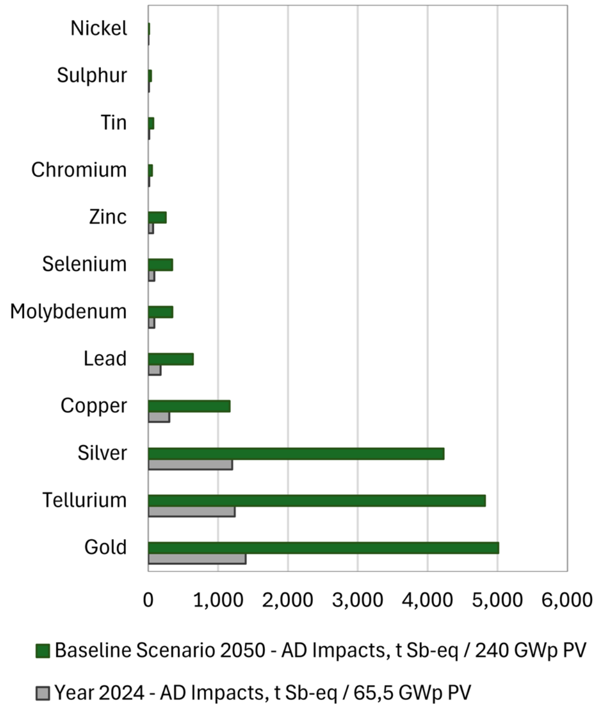

Fig. 4 Abiotic depletion (AD) impacts of the baseline scenario for PV deployment in the EU for the year 2050 compared to the year 2024. Cut-off: twelve biggest contributors.

3.2 Results of the thin-film scenario 2050

In the high thin-film scenario (Fig. 5), where CdTe and CIS technologies achieve a 30% market share, AD impacts demonstrate a slight change. Due to the higher tellurium demand the impacts increase to 5926 t Sb-eq (+23% compared to baseline) while gold decreases by −9% to 4586 t Sb-eq and silver by 17% (3504 t Sb-eq).

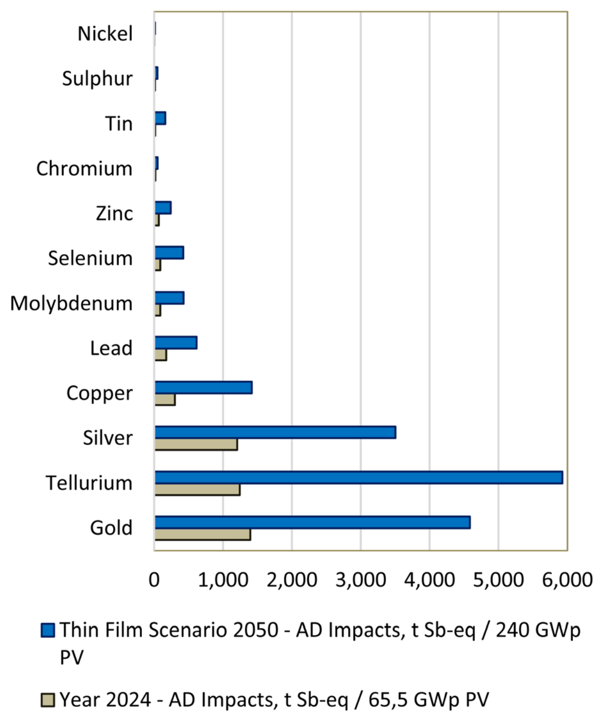

Fig. 5 Abiotic depletion (AD) impacts of the thin-film scenario for the PV deployment in the EU for the year 2050 compared to the year 2024. Cut-off: twelve biggest contributors.

The fact that projected tellurium demand in the high thin-film scenario is approximately five times higher than current European production highlights that, even if global reserves are sufficient, the EU would remain structurally import-dependent for this material. In combination with the very high AD impacts, this points to a persistent vulnerability of EU PV deployment to supply disruptions or price volatility in tellurium markets. Complete AD results and mass tables can be found in the SI materials.

3.3 Results of the year 2024 – the current AD impacts of PV

Fig. 4 and 5 demonstrate the current ADs of the PV deployment for the year 2024. The low share of thin-film technology reduces the amount of tellurium, making gold the most important material regarding the AD. Fig. 4 and 5 explicitly juxtapose AD results for 2024 and 2050 for the dominant materials. While it is expected that total AD impact increases with higher installed capacity, the comparison highlights that the relative dominance of tellurium, gold, and silver persists across time.

4 Discussion and limitations

The landscape of PV module production is primarily dominated by Asian producers, who accounted for over 90% of the market. China, in particular, led the way with a commanding 75% of the share in 2022.[28] The EU has solar cell production capacity of 0.76 GWp, while module production capacity is 8.28 GW. Europe contributed 1% to the production, while the USA and Canada combined for a 3% share.[1] However, even assuming increased EU PV capacities in the future and Net-Zero Industry Act targets, this structural dependency might remain for some materials.[29]

It is important to distinguish between two different questions. The first one is focusing primarily on expanding domestic cell and module manufacturing capacity, asking whether Europe can build enough factories to supply part of its own PV demand. Our analysis addresses a more upstream and long-term question: given certain PV deployment levels and technology mixes, which metals are most affected from a global geological depletion perspective, and how does this interact with Europe's structural import dependence? High AD impacts of tellurium, gold, and silver in our scenarios, therefore, signal that these metals are under strong long-term depletion pressure worldwide. Comparing the resulting PV-related demand in our scenarios to current European mining and production capacities is not meant to suggest that EU mine output alone determines supply security; instead, it illustrates that Europe would rely heavily on imports for precisely those metals that already show high global depletion pressure and geographically concentrated production. In this sense, AD impacts and European production capacities are complementary pieces of evidence, linking physical depletion risks with vulnerability of the European PV supply chain.

4.1 Supply risks of key materials for PV

For the main constituents of PV, glass (high-purity silica) and aluminium, crustal abundance is extremely high, and current extraction volumes are small compared to total reserves, which leads to effectively negligible AD impacts. On the other hand, metals such as silver, indium, gallium, or copper that are globally available in much smaller absolute quantities have much higher depletion risk. The LCA results indicate that tellurium, gold, and silver cause the highest AD impacts in both 2050 scenarios. Thus, to get a feeling for the order of magnitude, the mass flows of these materials were calculated based on the LCI of the analysed FU. Table 1 shows the results of the material demands of both scenarios. These three metals are introduced in this section; their production is examined and discussed in relation to European production capacities.

Table 1 Material demands of PV deployment based on the LCI of FU of 240 GWp installation of the year 2050

Material	Baseline scenario (t)	Thin-film scenario (t)
Tellurium	119	146
Gold	96	88
Silver	3569	2959

4.1.1 Tellurium. In the thin film scenario for 2050, tellurium made the largest contribution to the AD impacts. Tellurium is used in the production of CdTe for thin-film solar cells. In 2023, the world production of tellurium was estimated to be about 640 t. In 2022, China was the largest producer with 500 t with reserves of 6600 t.[30] EU's share in reserves is estimated to be 1.9% of the world.[31] The biggest EU producers are Sweden, Belgium, and Finland. For instance, Sweden produced approximately 25 t in 2021.[32] Tellurium is recovered mainly from copper anode slimes created during extraction from copper concentrates or can be mined as a by-product of gold mining. The demand for tellurium in PV applications could rise significantly under high deployment scenarios, potentially outstripping current supply capacities. In the baseline scenario, up to 119 t tellurium is needed in the final year. In the high thin-film scenario, the demand increases to 146 t, which is five times higher than the whole European production. Tellurium is used in thin-film PV, where it forms the primary light-absorbing semiconductor layer that directly converts sunlight into electricity. Besides PV, tellurium is used in thermoelectric devices and metallurgy.[31] End of life (EoL) recycling input rate in the EU is just 1%. This rate displays the contribution of recycled tellurium from EoL products to raw material demand (as the input of post-consumer material to the total material input).[33] 1% is extremely low, considering the fact that the EU's Critical Raw Materials (CRM) Act sets quantitative recycling benchmarks for 2030 of at least 25%.[32] Tellurium contents in PV are too low to be separated easily in the recycling processes. Enhanced recycling methods for CdTe panels, as well as exploration of telluride-rich gold mines, could mitigate supply risks.

4.1.2 Gold. In the baseline scenario, gold shows the highest AD impact. This value in the baseline scenario is higher than that of tellurium and silver. Gold is primarily used in PV cells as a contact material and in the inverters due to its excellent electrical conductivity and resistance to oxidation. In 2023, global gold mine production was approximately 3644 t, marking the highest level since 2018.[34] China was the largest producer, accounting for around 11% of the total global production, followed by Russia (10%) and Australia (9%). Europe has relatively modest gold production rates in global comparison. The EU's share in gold reserves is 2.2% of the worldwide reserves.[31] Gold production in the EU in the year 2024 was 23.9 t.[35] 96.3 t of gold is needed yearly in the baseline scenario with higher PV installation rates. In the thin-film scenario, the demand is slightly lower, 88.1 t. Both values exceed the European production by a wide margin. Recycling technologies, such as electrochemical processesX, offer the potential for recovering gold efficiently from decommissioned panels. The overall EoL recycling input rate in the EU is 24%, which is relatively high compared to tellurium and almost achieves the EU goal of the CRM act.[36]

4.1.3 Silver. Silver is the third biggest contributor in the AD results in all scenarios. Silver is predominantly used in c-Si PV modules as screen-printed contact paste that forms the front-side metallization grid for efficient current collection from the solar cell surface and inverter electronics.[37] The estimated global production of silver in 2023 was around 26 000 t.[38] Major silver-producing countries include Mexico (27%), Peru (13%), and China (13%).[30] Europe's silver production is 7.5% compared to global production. 4000 t of silver production is situated in the EU.[32] Poland produced approximately 1400 t of silver in 2023, making it the largest producer in Europe (approximately 62% of the European sourcing).[31] In the thin-film scenario, annual demand for silver is 2959 t, and in the baseline, 3569 t, which makes up 87% of the European production. The EoL recycling input rate for silver in the EU is 19%, 6% lower than the EU CRM act goals. In addition, low recycling rates limit the ability of secondary supply to mitigate such risks, thereby reinforcing the implications of the elevated AD results.

These production ratios are not meant as standalone indicators, but as contextual evidence of potential supply stress for those materials that already show high AD impacts in this LCA study. When annual PV-related demand approaches current EU mine production, even moderate disruptions in imports or production could translate into supply risks for PV manufacturing in Europe.

4.2 Comparison to the EU's critical raw materials approach

Supply risk of critical metals for the European Industry is covered by the CRM Act. CRM methodology and AD represent distinct approaches, addressing different aspects of resource evaluation through fundamentally different assessment paradigms and methodological foundations. CRM evaluates the materials based on two factors: economic importance and supply risk. Economic importance measures the significance of materials through value-added analysis corrected by substitution indices. Supply risk evaluates disruption through supply concentration, geopolitical factors, and import reliance metrics.[32] The methodology employs threshold-based classifications (economic importance $\geq$ 2.8 and supply risk $\geq$ 1.0) to designate materials as critical, focusing on short to medium-term supply security rather than long-term physical depletion.[39] This is the main difference from AD, which uses physical parameters such as extraction rates and crustal reserves. Some developments include strategies to integrate both approaches, which multiply AD factors by normalized CRM criticality factors, allowing combined assessment of physical depletion and supply security risks.[40]

However, this normalization process may create situations where materials with moderately high criticality receive unexpectedly large impact multipliers, potentially overemphasizing their importance compared to their actual supply security significance. Also, the coverage of the materials is not identical in AD and CRM data sets, which limits the methodology's comprehensive applicability.

4.3 Limitations

Projecting PV deployment and LCI for the year 2050 faces significant limitations that affect its accuracy. The scenario projection assumes linear scaling relationships between PV capacity and material demand, which may not account for potential technological breakthroughs, material substitution innovations, or circular economy developments that could alter resource requirements. Innovative PV technologies such as perovskite, multi-junction cells, or hybrid devices are currently under development. Deployment of these technologies is uncertain, as is the deployment rate of PV in general. The material consumption based on the learning rates is uncertain for the future; the feedback loop between deployment and learning rates could become a self-fulfilling prophecy by limiting necessary accumulations.

Additionally, efficient EoL management of PV modules is crucial to increase closed-loop recycling rates for *e.g.*, tellurium, gold, and silver. However, the shares of recycling are hard to predict. Especially since the production primarily takes place in China, and geographic mismatch forces questions on the recycling possibilities in Europe. As a reaction to this issue, the CRM Act established ambitious mandatory recycling targets specifically designed to enhance supply chain resilience, including PV.[36] Given that silver and gold are among the costliest elements in PV cells, further advancements in material efficiency and recycling that go beyond the estimated assumptions are anticipated for the future. Also, copper is emerging as a potential replacement for silver due to its lower cost and good electrical conductivity.[41] Including EoL processes as a separate stage of the LCA would thus enhance the quality of the LCA results compared to incorporating a simplified representation of closed-loop recycling rates (reduction of primary material flows).

Used LCI is based on upstream supply chains of PV manufacturing rather than isolated material compositions of finished products, meaning that resource depletion impacts reflect the entire production network, including raw material extraction, processing, transportation, and intermediate manufacturing stages. The differentiation of upstream supply chains and identification of specific resource consumption within these complex multi-stage processes should be the subject of further research, as current LCI methodologies aggregate impacts across multiple production tiers without providing granular visibility into individual supply chain alternatives.

The AD characterization factors rely on reserve estimates and production data that are subject to geological uncertainty, particularly for scarce materials. From the methodological point of view, reserve-to-production ratios are based on past data, which also cannot predict future technological innovations or sudden geopolitical shifts. Additionally, AD calculations face high uncertainty due to unknown reserve estimates and squared reserve terms in formula.[15] Over the years, ultimate reserve estimates have changed very little, reflecting their basis in long-term geological information rather than current market conditions. In contrast, annual production is highly dynamic and follows technological and societal trends. Addressing these gaps in the methodology requires dynamic models integrating geopolitical and technological frameworks that are updated regularly.

Additionally, a critical supply constraint might emerge from the fact that tellurium is produced almost entirely as a by-product of copper refining, while silver is also significantly dependent on copper production as a by-product source. This creates a fundamental supply bottleneck if copper demand does not increase proportionally with PV deployment, as these critical materials cannot be independently scaled up to meet growing photovoltaic requirements.[32]

And yet, examining the upscaling scenarios and import dependency goals for raw materials such as tellurium, gold, and silver, the EU's target of domestic production remains unmet.

5 Conclusions

This study presents an assessment of PV deployment scenarios across the EU through 2050. Using LCA methodology with AD characterization factors, material requirements across baseline c-Si-dominated and high thin-film deployment scenarios were analysed, revealing supply constraints that could significantly hinder Europe's renewable energy transition.

The results of the study demonstrate that tellurium, gold, and silver represent the most important materials for EU PV deployment in both thin-film and base line scenarios by 2050. These three materials collectively account for over 80% of total resource depletion impact across all PV scenarios. The EU's minimal share of global reserves of these materials presents substantial supply security risks for European PV manufacturing. Moreover, processing of these materials is geographically concentrated in a limited number of producer countries, further increasing the EU's vulnerability to geopolitical and market disruptions.

Although recycling offers potential mitigation, current EoL recycling input rates remain low. To fulfil Europe's commitment to the circular economy, increasing closed-loop recycling and reducing material intensity per kWp through technological improvements and substitutions is essential. Systematic assessment of material substitution possibilities across all PV components would identify additional flexibility in the material-technology system.

Future research should also investigate alternative PV technologies, including organic photovoltaics and perovskite-silicon tandems. This could reveal pathways that fundamentally alter material requirements and should be assessed in future research. Only by following resource efficiency and circular economy principles can Europe realize the full potential of PV as a sustainable energy source.

Author contributions

Conceptualization and methodology: Olga Kanz, Christina Wulf, Petra Zapp; investigation, visualization, and writing: Olga Kanz; writing – review and editing: Christina Wulf, Petra Zapp.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5se01467k.

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