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Full length article

Photovoltaics under constraints: Dynamic material flows, supply pressures and circularity in the Eastern Mediterranean and Middle East

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A R T I C L E I N F O

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A B S T R A C T

The Eastern Mediterranean and Middle East (EMME), comprising 17 countries, has exceptional solar energy potential. Regardless of whether countries follow business-as-usual or coordinated net-zero energy transition pathways, unprecedented photovoltaic (PV) deployment is expected in the coming decades. However, raw material implications of this deployment remain underexplored. This study applies a dynamic material flow analysis to quantify deployment-driven material inflows, in-use stocks, and end-of-life outflows of PV systems in the EMME region over the period 2000–2055. The study further combines these results with supply pressure and circularity analyses.

Results show that the region is already a major consumer of PV raw materials. Deployment, especially under nationally fragmented energy planning, is projected to deepen the pressure on primary demand. Regional energy integration towards the net-zero target reduces cumulative PV material stocks by about 30% compared to a nationally fragmented pathway. Germanium and tellurium fall under the high-risk category. Under High Circularity, with collection and recycling rates gradually rising to upper-bound levels by 2055, primary demand for the majority of PV materials can be avoided by 60%-80% in specific periods. For silver and germanium, recovered quantities can exceed projected demand.

1. Introduction

Photovoltaic (PV) systems are a central pillar of the global renewable technology deployment in the transition to a low-carbon and environmentally sustainable energy systems. Their modularity, scalability and declining costs make them attractive even in regions with modest solar resources. However, large-scale deployment raises concerns regarding material availability, affordability, geopolitical dependencies, and supply chain vulnerabilities (Gielen, 2021; Hund et al., 2023; IRENA, 2023; IEA, 2021). In response, advanced economies have increasingly integrated critical material strategies and regulatory frameworks into policy agendas to enhance supply security and resilience (see Supplementary Information – SI, Table ST1). However, despite growing global attention to material supply risks, the Eastern Mediterranean and Middle East (EMME[1]) remains largely absent from this strategic landscape. This is particularly notable given the region's exceptional solar potential (Kiriakidis et al., 2024) and national climate pledges signalling accelerated PV deployment (Taliotis et al., 2023). The region has yet to establish material governance frameworks capable of ensuring environmental, social and economic sustainability across the full life cycle of these systems. The PV sector in the region is also evolving heterogeneously, with some countries positioning themselves as key PV system component manufacturers, while others remain heavily reliant on imports (ST5). However, unlike structurally prepared regions, most EMME countries lack strategies to secure their transition and develop circular value chains (ST14). As a result, the long-term sustainability of the region's energy transition— particularly in terms of critical material availability and its implications for the global sustainable balance between primary extraction and secondary material recovery – remains underexplored in the literature.

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[1] The Eastern Mediterranean and Middle East (EMME) region, introduced by the Cyprus Institute (Lelieveld et al., 2012) refers to countries sharing common climatic vulnerabilities across the Eastern Mediterranean and Middle East. Formalised through the EMME Climate Change Initiative (EMME-CCI) at COP27, it includes the United Arab Emirates, Bahrain, Cyprus, Egypt, Greece, Israel, Iraq, Iran, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, and Turkey. *Supplementary Information* Section 2 *provides full regional context.*

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Globally, the material requirements of the sustainable energy transition have received significant attention (Carrara et al., 2020; Foster et al., 2025; Grandell et al., 2016; Hund et al., 2023; Valero et al., 2018; Watari et al., 2019; Wellmer et al., 2019; Zhou et al., 2020), with a growing body of work applying dynamic Material Flow Analysis (MFA) to assess time-dependent material inflows, stocks and end-of-life outflows at the national scale (Kucukvar et al., 2018; Lallana et al., 2024; Nassar et al., 2016; Savvidou and Johnsson, 2023; Tasseven et al., 2026;

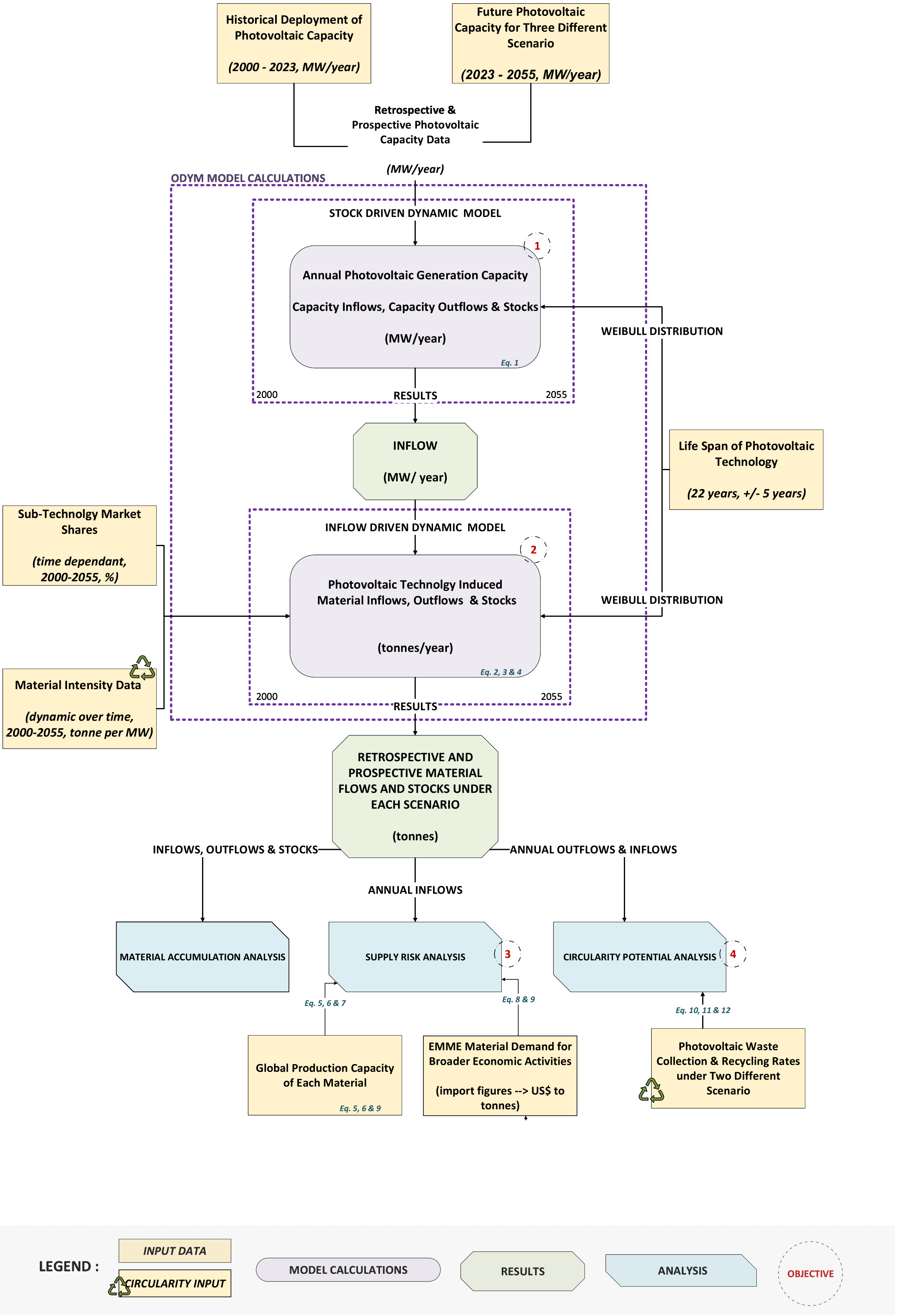

Fig. 1. Analytical framework: PV material flows, risks, and circularity in EMME.

van Oorschot et al., 2022; Viebahn et al., 2015). Several studies have examined the energy transition and PV deployment in parts of the EMME (Taliotis et al., 2023; MESIA, 2025) which provide important insights into future PV capacity expansion and system-level dynamics. In parallel, a limited number of studies have quantified material requirements for specific EMME countries or technologies, such as Cyprus and Turkey (Tasseven et al., 2026; Kucukvar et al., 2018). However, these studies are primarily limited to individual national contexts and therefore do not capture the cumulative effects of simultaneous energy transitions across the region, nor the resulting region-wide material demand and associated supply pressures that characterize the EMME context.

Given current uncertainty and limited availability of consistent data on regional PV manufacturing inputs this study focuses on deployment-side material flows, which are more reliably quantifiable and offer an important first step in understanding regional material needs. We develop a dynamic MFA framework to quantify PV-related material flows, supply pressures and circularity potential for the EMME region. To the best of our knowledge, this is the first study to apply such an approach to the region, covering 17 countries and providing a comparable analytical basis with existing assessments for other regions, including the EU (Foster et al., 2025) and major economies such as the United States (Khalifa et al., 2021) and China (Wang et al., 2019). Beyond extending existing approaches to a new geographic context, the study integrates diverse datasets into a unified framework to provide novel insights that can inform the region's sustainable energy transition. Specifically, national energy transition pathways are integrated into a regional framework to analyse spatial and temporal material dynamics while the MFA outputs are combined with a fair-share-based supply risk assessment and scenario-based circularity analysis. Accordingly, the analysis in this paper is guided by the following four questions:

1. How national versus regional energy transition pathways shape the total and spatial accumulation of PV materials;
2. What are the timing and scale of material inflows and outflows, and whether they signal a shift toward circularity;
3. Which materials are most at risk of exceeding the EMME region's fair share of global supply; and
4. To what extent end-of-life material recovery can reduce primary demand under different circularity scenarios.

2. Methodology

We apply a retrospective and prospective dynamic MFA to quantify PV system material inflows, in-use stocks, and end-of-life outflows under different energy transition scenarios in the EMME region between 2000 and 2055 (Fig. 1). MFA results are used as a foundation for two complementary assessments: (i) circularity potential, by combining projected outflows with collection and recycling assumptions, and (ii) supply risks, by benchmarking scenario-based material inflows against global production capacity.

This study employs a combination of stock-driven and inflow-driven modelling approaches (Graedel, 2002; Müller et al., 2014) and follows the standardized modelling package offered by ODYM, the Open Dynamic Material Systems Model (Pauliuk and Heeren, 2020). Fig. 1 shows the core MFA modules (dashed boxes) and their links to data inputs for further analysis.

2.1. *Objective 1: estimating the capacity inflows*

Historical deployment data (2000–2023) were derived from IRENA (2024) to establish the regional PV baseline (expressed in MW). The prospective capacity projections were derived from regional energy scenarios (Taliotis et al., 2023), except for Cyprus (CY NECP, 2024) and Greece (GR NECP, 2025) where updated national pledges were used. The following three scenarios were chosen to capture varying degrees of climate ambition and regional cooperation (ST7).

- Reference Scenario (REF): Baseline Scenario aligned with the latest Nationally Determined Contributions and/or National Energy and Climate Plans of EMME countries. It assumes no additional climate targets and limited electricity trade (only existing interconnections). Countries primarily rely on domestic generation to meet demand.
- Reference Trade Net-Zero Scenario (RTNZ): It builds on the REF Scenario but assumes a linear path to net-zero emissions by 2050 in the electricity sector, again with limited trade potential.
- Unrestricted Trade Net-Zero Scenario (UTNZ): It assumes full regional electricity trade and infrastructure expansion to achieve net-zero emissions by 2050 in a cost-optimal way, prioritizing resource sharing and large-scale electricity interconnection investments. While this scenario represents a normative upper-bound pathway, its realization may be constrained by institutional, political, and geopolitical barriers in the EMME region.

We employed a stock-driven approach, whereby inflows are derived from desired cumulative installed capacity, determined using a Weibull lifetime distribution.

$$CI^{sc}_{PV}(t) = CS^{sc}_{PV}(t) - \sum_{\tau=t_0}^{t-1} CI^{sc}_{PV}(\tau) * \propto(t-\tau) \tag{1}$$

Where;

- $CI^{sc}_{PV}(t)$: Capacity inflow in year "t" under scenario ("sc")
- $CS^{sc}_{PV}(t)$: Target cumulative installed capacity in year "t" for scenario ("sc")
- $\propto(t-\tau)$: Survival function representing the share of capacity installed in year "τ" that still operates in the year "t", derived from Weibull distribution.

  "t_0" : Initial modelling year (2000)

2.2. *Objective 2: capacity inflows to material flows and in-use stocks*

PV systems are typically composed of three main subsystems: the module, structural components, and electrical components. The PV module itself is the most material-intensive component and is represented mainly by four technology types: crystalline silicon (c-Si) and thin-films, namely amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) (Grandell et al., 2016; Zhou et al., 2020). Advanced technologies (e.g. HJT, TOPCon, and OPV) were excluded from the scope.

Aluminium (Al) and copper (Cu) were included in our analysis for structural components and are treated as technology-invariant in terms of tonnes per MW. Silicon (Si), silver (Ag), cadmium (Cd), tellurium (Te), germanium (Ge), indium (In), gallium (Ga), and selenium (Se) are included as PV-specific materials. Technology-specific dataset from peer-reviewed literature and institutional sources were applied (expressed in tonnes of material per MW of PV installed).

Between 2000 and 2055, structural materials were assumed to experience minor time-dependent material intensity reductions. For PV-specific materials, we assumed relatively greater improvements in material intensities consistent with the literature (Carrara et al., 2020; Zhou et al., 2020). We adopted technology-specific market share assumptions to reflect the evolving composition of PV deployment in the EMME region (Elshkaki and Graedel, 2013; Viebahn et al., 2015; Carrara et al., 2020; Fraunhofer, 2025). Full datasets are provided in the SI (S3.4-S3.5).

An average operational lifetime of 22 years with a standard deviation of ±5 years was assumed to reflect the regional operating conditions (Atia et al., 2023; Frick et al., 2020; Guanghua et al., 2025; Jordan and Kurtz, 2013).

The annual material inflow "$I_m(t)$" is calculated as the product of scenario-specific capacity inflow “$CI^{sc}_{PV}(t)$”, the market share of each PV sub-technology “$MS^{sc}_{tech}(t)$”, and the material intensity of material “m” in that technology “$MI^{sc}_{m,\ tech}(t)$”:

$$I_m(t) = CI^{sc}_{PV}(t) * \sum_{tech} \left(MI^{sc}_{m,\ tech}(t) * MS^{sc}_{tech}(t) \right) \tag{2}$$

The in-use stock “$S^{sc}_m(t)$” represents the accumulated material embedded in active PV systems and is calculated using an inflow-driven approach with a Weibull distribution.

$$S^{sc}_m(t) = \sum_{\tau = t_0}^{t} I^{sc}_m(\tau) * \propto(t - \tau) \tag{3}$$

The material outflow “$O^{sc}_m(t)$” is then derived from the mass balance, calculated as the difference between the annual inflow and the change in stock:

$$O^{sc}_m(t) = I^{sc}_m(t) - \Delta S^{sc}_m(t) \tag{4}$$

2.3. Objective 3: initial supply risk assessment

To assess the supply risk in the absence of a regional criticality study, we adopted a threshold-based “fair-share” benchmarking approach (Carrara et al., 2020). This methodology compares the region’s material demand to what could be considered as its fair share of global production. The “fair share” in question is calculated using the EMME region’s contribution to global GDP as a weighting factor. This metric is not intended as a normative measure of equity, but rather as an economic proxy to relate regional demand to global production capacity within the modelling framework.

The fair share threshold for the EMME region (FS_{emme}) is calculated as the region’s share of global GDP.

$$FS_{emme} = \frac{GDP_{emme}}{GDP_{global}} \tag{5}$$

To find material demand relative to global production, for each material “m”, year “t”, and scenario “sc”, we calculated the supply pressure indicator “$SPI^{sc}_m(t)$”, defined as the share of current global production required to meet the EMME region’s material demand.

$$SPI^{sc}_m(t) = \frac{I^{sc}_m(t)}{GP^{global}_m} \tag{6}$$

Where:

- “$I^{sc}_m(t)$” is the annual inflow of material “m” from the MFA model results
- “GP^{global}_m” is the global annual production capacity of material “m”.

Risk categories are defined through the relative pressure ratio, comparing demand to the fair share threshold, and are categorized as low (<0.5), moderate (0.5–0.75), elevated (0.75–1.0), and high (>1.0, demand above fair share) (ST13).

$$Relative\ Pressure^{sc}_m(t) = \frac{SPI^{sc}_m(t)}{FS_{emme}} \tag{7}$$

An economy-wide baseline assessment for 2022 is also conducted to contextualize PV-related material supply (ST9-ST11).

The total material demand ($TMD_{m(2022)}$) in the entire EMME economy in 2022 was then calculated as:

$$TMD_{m(2022)} = IM_{m\ (2022)} + PV_{m\ (2022)} \tag{8}$$

where (2022) denotes values corresponding to the reference year of the baseline assessment.

This total was expressed as a share of current global production capacity “GP^{global}_m” using:

$$SPI_{m\ (2022)} = \frac{TMD_{m(2022)}}{GP^{global}_m} \tag{9}$$

2.4. Objective 4: assessment of circularity potential

We modelled two circularity scenarios: a Low Circularity Scenario (LCS) and a High Circularity Scenario (HCS). Circularity activities are assumed to commence in 2025. An initial collection rate of 20% was assumed, increasing by 2055 to 45% in the LCS and 85% in the HCS. Assumptions are based on a review of regulatory frameworks and current practices (ST14-ST15). Material specific recycling efficiencies follow current averages (EU RMIS, 2024) in the LCS and long-term technical potentials in the HCS (Earthworks, 2019; ESA, 2019; Preet and Smith, 2024).

We used the annual end-of-life outflows from the dynamic MFA, circularity potential of each material is quantified with the following three steps:

a) **Collection phase**: A fixed share of each material’s outflow is assumed to be collected based on the scenario-specific (LCS & HCS) collection rate:

$$Collected\ Quantity^{sc}_m(t) = Outflow^{sc}_m(t) * \frac{Collection\ Rate^{sc}_m(t)}{100} \tag{10}$$

b) **Recycling phase**: A subset of the collected material is assumed to be successfully recovered based on the recycling rate:

$$Recovered\ Quantity^{sc}_m(t) = Collected\ Quantity^{sc}_m(t) * \frac{Recycling\ Efficiency^{sc}_m(t)}{100} \tag{11}$$

c) **Primary Demand Avoided (PDA):** This is the share of material requirements met by recovered quantities where scenario-specific inflows - $I^{sc}_{m,\ t}$ (i.e. virgin material requirement for new PV deployments in year t) could be substituted by $Recovered\ Quantity^{sc}_m$ in that year.

$$PDA^{sc}_{m,\ t}[\%] = \frac{Recovered\ Quantity^{sc}_{m,\ t}}{I^{sc}_{m,\ t}}\ x\ 100 \tag{12}$$

3. Results

3.1. Material accumulation

Fig. 2 shows country-level in-use material stock accumulation across the EMME region under the three scenarios from 2000 to 2055. Under the REF, total stock accumulation reaches approximately 12.34 Mt in 2054, the highest among the three scenarios. This reflects that, in the absence of a net-zero constraint, countries deploy more PV capacity compared to RTNZ, where part of the demand is instead met by other renewable energy investments such as wind and concentrated solar power (Taliotis et al., 2023). Conversely, the RTNZ scenario results in a lower peak in a different year, with a cumulative stock of around 8.76 million tonnes in 2050. These results reflect the efficiency gains through technological shifts (net-zero targeted investments), as well as improved demand and supply of electricity management through limited trade activities between the countries in the region which reduces the total PV capacity required to meet electricity demand. Lastly, the UTNZ scenario results in a peak cumulative stock of approximately 9.16 million tonnes in 2054. The results for this scenario are very close to those of the RTNZ scenario, although still substantially lower than the stock projected

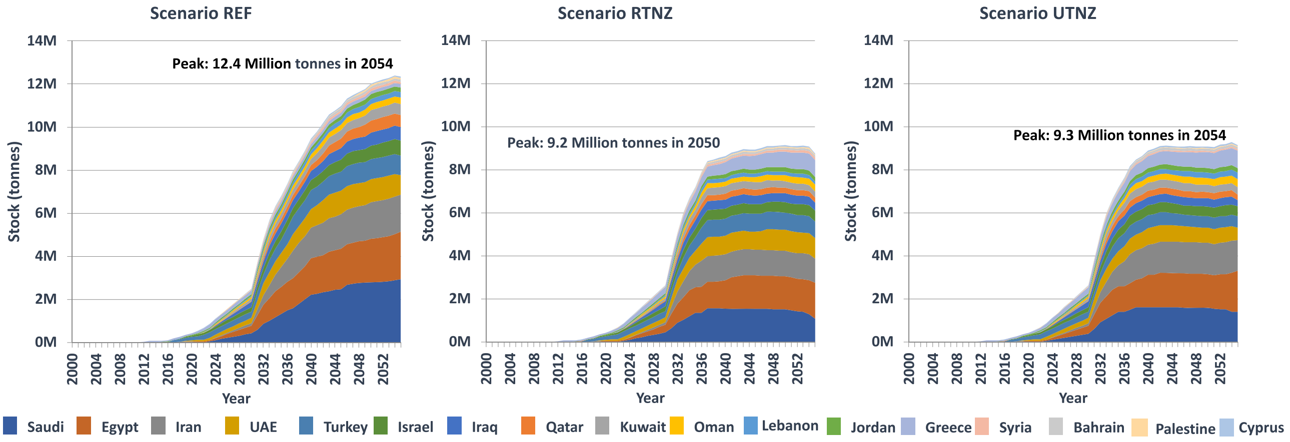

Fig. 2. Country-specific in-use stock accumulation in the EMME region under REF, RTNZ and UTNZ.

under the REF.

Overall, our results show that the primary material accumulation of PV systems for the region can be effectively reduced by 26 - 29% through regional electricity trade and cooperation. Comparisons between REF and the integrated scenarios (RTNZ, UTNZ) show that coordinated transition policies with electricity trade reduce total PV capacity requirements through a combination of; (i) technology substitution, (ii) improved temporal coordination of investments and (iii) spatial optimisation of deployment, including the concentration of PV generation in higher-resource regions as reflected in country specific capacity factor in the underlying energy system model (Taliotis et al., 2023). As a result, capacity investments and material accumulation are redistributed across the countries – shaping both total demand for and spatial distribution of materials across countries. Material accumulation for each EMME country under different scenarios (2000–2055) is provided in the SI (ST16, SF7–8)

3.2. *Material flows*

3.2.1. *Inflows and outflows*

To observe how the timing and magnitude of inflows and outflows vary across the three energy transition pathways—REF, RTNZ, and UTNZ— material flow patterns (expressed in tonnes) are shown in Fig. 3. Total inflows, outflows and crossover years (in which annual outflows surpass inflows) are reported in SI (ST11).

Inflows dominate between 2030 - early 2040s which is the peak phase of PV deployment, driven by the rising electricity demand and accelerated decarbonization. The pronounced increase in inflows also reflects the timing of deployment in the underlying energy system scenarios as they are directly linked to annual capacity additions (Taliotis et al., 2023). In the same period, aluminium and copper have the largest shares due to their structural/electrical roles in PV systems regardless of the sub-technology type (cSi, CdTe, aSi or CIGS). As regards silicon, although it is a PV-specific material, its requirements are similarly high in all scenarios since the material serves as the primary semiconductor in both aSi and cSi technologies.

Although minor in mass, PV-specific materials such as silver, tellurium, cadmium, indium, gallium, germanium, and selenium carry greater strategic weight. Their supply risks remain a central concern for long-term deployment strategies as they play a critical role in determining the sustainability and resilience of PV supply chains due to limited global availability and concentration of production.

Outflows remain negligible in the early decades but accelerate after 2040 as the first wave of installed systems reaches the end of their useful life. For most of the materials, crossover points (outflows > inflows) begin to emerge (ST17), marking a transition from a growth-driven phase towards a more mature system in which end-of-life flows become increasingly significant. This transition is primarily driven by the interaction between cumulative installed capacity and module lifetime distributions, as large volumes of previously installed systems reach end-of-life, while inflows stabilise or grow at a slower rate depending on the scenario. Declining material intensities further contribute to this shift by reducing inflows per unit of new capacity. Overall, these phase of the modelled timeline indicate potential secondary recovery opportunities that could shift the transition from linear to a circular resource use pattern.

Under REF, crossover points generally occur later, closer to 2055, particularly for high-volume materials like aluminium, copper, and silicon. In contrast, under RTNZ and UTNZ, where regional trade is coupled with net-zero targets, crossovers occur earlier (between 2042 and 2045 under RTNZ and UTNZ, several years earlier than under REF). This reflects more efficient and coordinated deployment strategies under RTNZ and UTNZ, where regional electricity trade reduces redundancy in national investments and lower overall PV capacity requirements. Under these scenarios, material inflows are reduced compared to REF, and given similar lifetime assumptions across scenarios, crossover points occur earlier because inflows decline relative to outflows.

For instance, under UTNZ, aluminium and copper begin to show net outflows several years earlier than in REF. Similar trends are observed for silicon and silver. Overall, the earlier cross-over years under RTNZ and UTNZ show how coordinated planning towards net-zero and cross-border electricity trade can both lower the total material stocks (as shown in Section 3.1.) and advance the timing of secondary material availability, thereby increasing their potential to offset primary demand.

3.2.2. *Initial supply risk assessment*

Projected annual PV material demand is assessed relative to the current global supply to identify potential bottlenecks. Fig. 4 illustrates the relative demand for each material across all modelled scenarios. Detailed relative pressure values (cf. Eq. (7)) and risk classifications for 2023 (baseline), 2031 (peak inflows), 2040 and 2050 are provided in SI (ST12). The red line at 4.9% indicates the EMME region’s fair share threshold.

Results show that most materials remain within the low-risk category. Structural PV materials (aluminium and copper) are no exception. Among PV-specific materials, silicon remains at “moderate risk”, while tellurium and germanium reach “high risk”, especially in year 2031 – corresponding to the first wave of elevated capacity investments. The region’s projected PV deployment in 2031 would require more than four times its fair share of global germanium production. As this trend appears in all scenarios, germanium emerges as a high-risk material within the context of this supply pressure indicator. Germanium is used in a-Si technologies, whose market share and material intensity are assumed to decline over time in our model. Nevertheless, the observed supply pressure is driven by the combination of (i) very limited global production (~140 tonnes annually) and (ii) near-term demand peaks during early deployment phases. Hence, even relatively small PV demand can lead to high Supply Pressure Indicators (Eq. (6)) within this context.

Tellurium also demonstrates elevated supply pressure relative to the global production capacity within this framework, especially in 2031

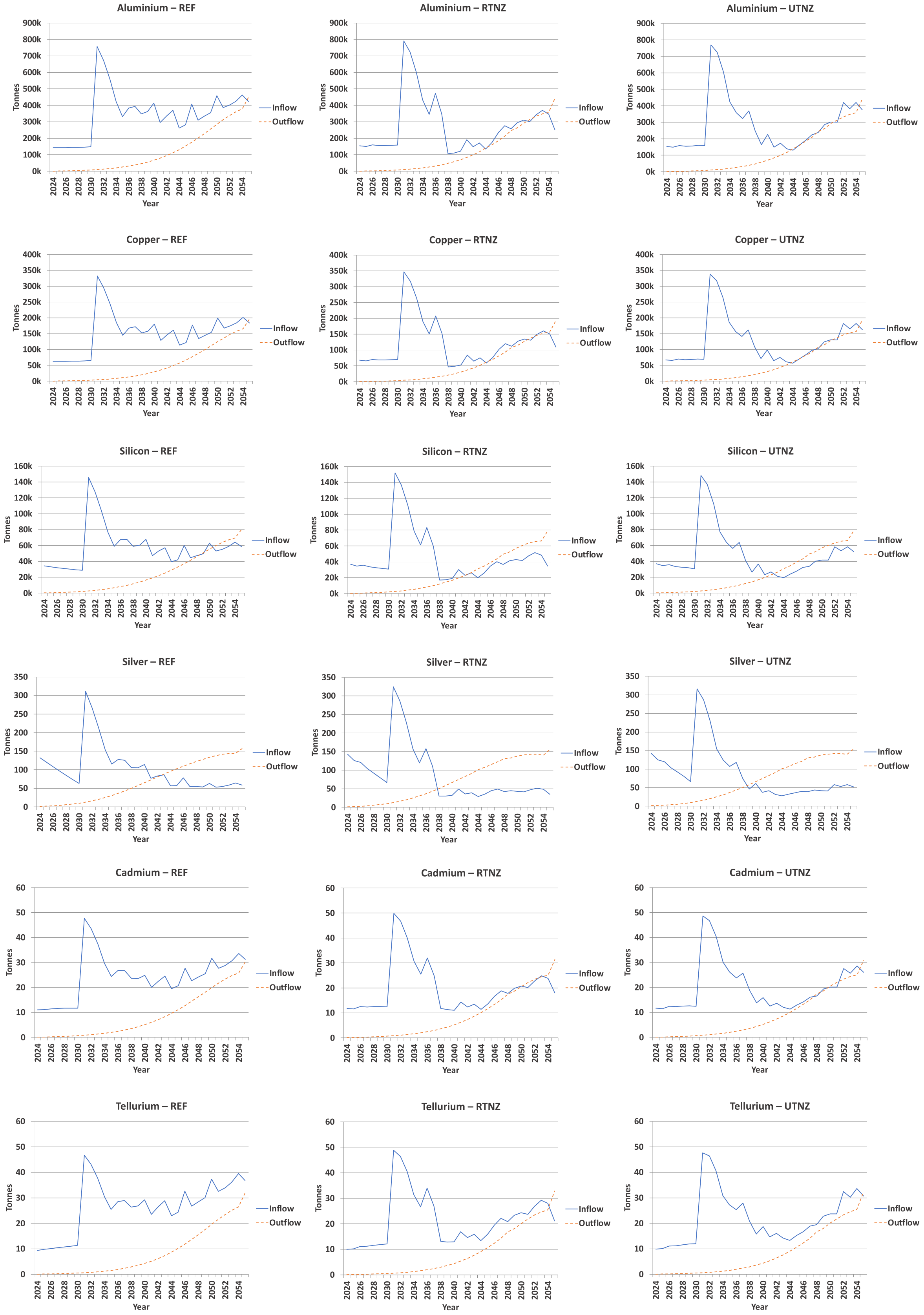
Aluminium – REF
Aluminium – RTNZ
Aluminium – UTNZ
Copper – REF
Copper – RTNZ
Copper – UTNZ
Silicon – REF
Silicon – RTNZ
Silicon – UTNZ
Silver – REF
Silver – RTNZ
Silver – UTNZ
Cadmium – REF
Cadmium – RTNZ
Cadmium – UTNZ
Tellurium – REF
Tellurium – RTNZ
Tellurium – UTNZ

Fig. 3. Temporal evolution of inflows (blue) and end-of-life outflows (orange) of PV-system materials in the EMME region under the REF, RTNZ and UTNZ scenarios.

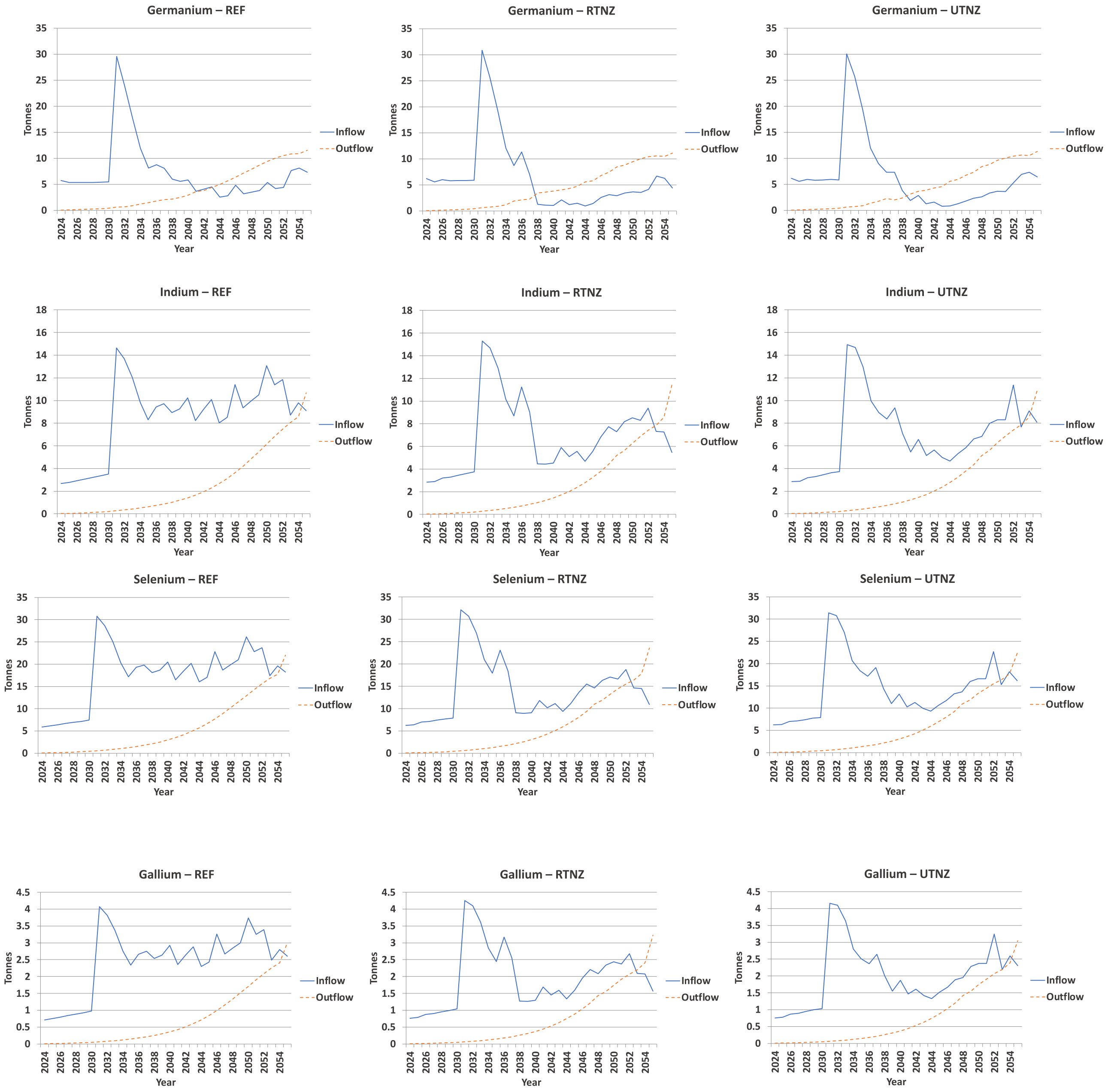

Fig. 3. (*continued*).

(up to one and a half times its fair share) and remains in the elevated-to-high-risk range through 2040 and 2050 especially under REF and UTNZ scenarios. The remaining materials fall under the low-risk range with pressure increasing during certain periods.

Fig. 5 illustrates the relative pressure of total material demand over the global production capacity. The red line in Fig. 5 represents the fair share threshold.

Accordingly, the results show that even prior to large-scale PV expansion, aluminium, copper, silver and germanium already exceeded the threshold, while tellurium stayed at the moderate risk range. Results indicate potential structural supply pressures when interpreted through the fair-share framework used in this study. Taken together, the 2022 static assessment confirms that supply pressure from the EMME region's demand for these materials is not solely a future concern linked to PV expansion but is a potential structural feature of the region and its material consumption profile. Broader policy implications are discussed in Section 4.

3.2.3. *Circularity potential*

We focus our analysis on outflows under the RTNZ scenario, as it represents the most policy-plausible energy transition pathway (not blind to climate goals, not very ambitious in terms of integration) given current institutional and geopolitical constraints that may limit the feasibility of UTNZ scenario. The Low Circularity Scenario (LCS) and the High Circularity Scenario (HCS) were compared and the full results for the projected total material recovery (TMR) and primary demand avoided (PDA,% of inflows) are presented in SI (ST20).

Overall, recovery volumes in both circularity scenarios remain modest for all materials until 2040 reflecting; (i) the combined effect of the projected peak in PV deployment between 2030–2040 and the long operational lifetimes of PV systems, which delay the end-of-life outflow; (ii) underdeveloped collection and recycling systems and evolving regulatory frameworks assumed by the circularity scenarios. From 2040 onwards, however, recovered quantities increase significantly, particularly under HCS.

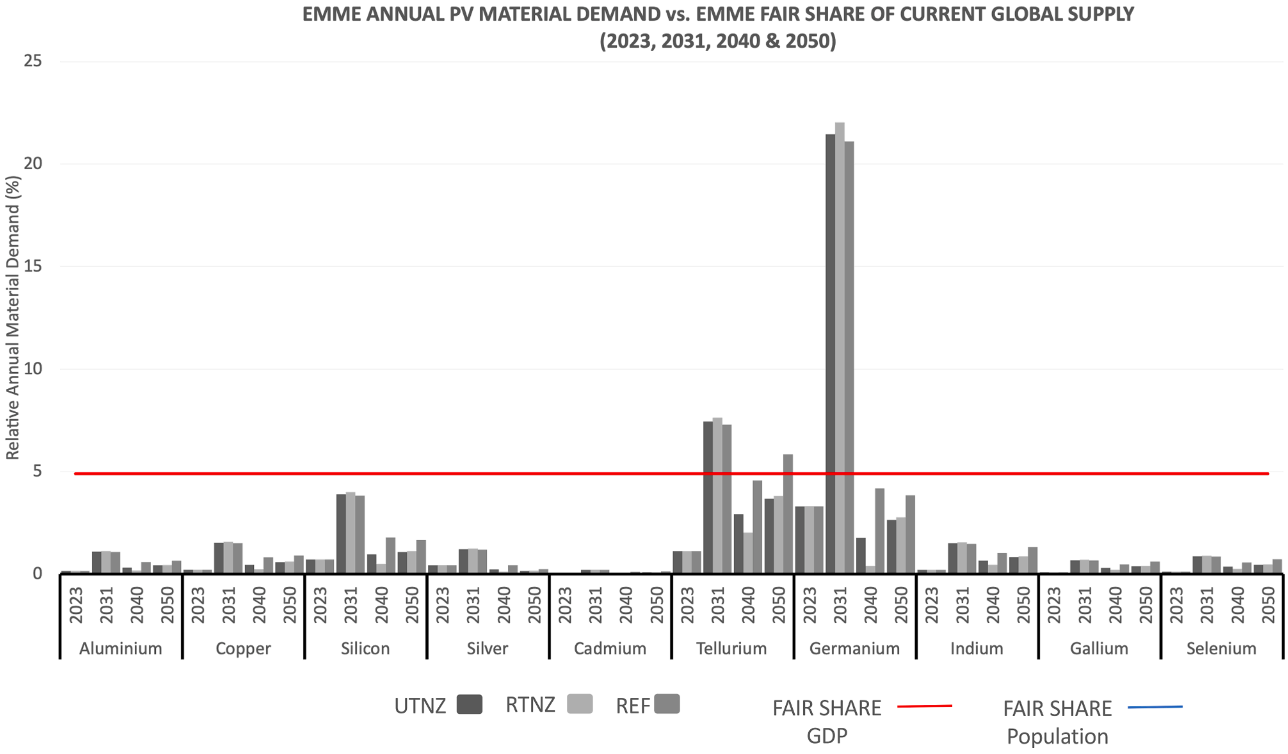

Fig. 4. EMME annual PV material demand vs. EMME fair share of current supply in years 2023, 2031, 2040 & 2050 across all scenarios.

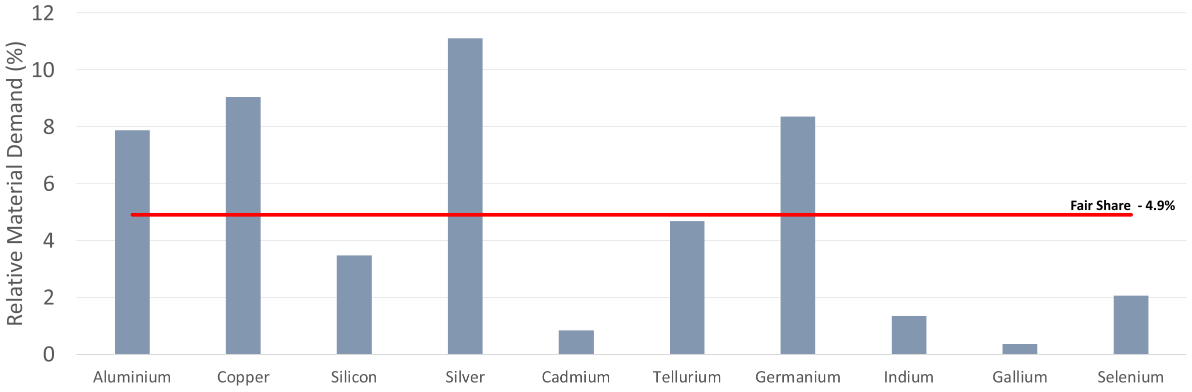

Fig. 5. EMME material demand vs. EMME fair share of current global supply in 2022.

Between 2000 and 2055, total recovered volumes under HCS reach 2.2 Mt aluminium and 870,000 t copper, compared to 1.2 Mt and 230,000 t respectively under LCS. While these structural materials dominate by mass, the relative benefits are more prominent for PV-specific materials.

Focusing on the high-risk materials tellurium and germanium, investment in dedicated PV recycling infrastructure together with supporting regulatory frameworks and policy incentives, can reduce their primary demand by 62% and 129% respectively in 2050–2055 period. In other words, while more than the half of tellurium needs can be met, secondary supply could fully cover and even surpass new demand for germanium by 2055.

Fig. 6 visualizes the material flows under the HCS and captures the whole system processes within the scope of this study. Outflows are divided into collected and uncollected modules. Collected modules are then split into recycled and residual fractions. PV-specific materials are grouped at the early stages, while final recovered quantities are presented by material type.

The contrast between structural material flows (aluminium & copper), which dominate the absolute mass (~13.5 Mt combined), and the flows of PV-specific materials, which although smaller in volume (~1.6 Mt) carry moderate to high risk, is evident from the diagram. However, as noted previously, while the mass benefits are highest for structural materials, the strategic gains are in high-risk elements. cSi technology stands out as the dominant sub-technology (with ~14 Mt of associated material flows) compared to CdTe, a-Si and CIGS (~1.25 Mt combined). About 15 Mt of materials enter the system between 2000 and 2055 – 9 Mt remain as active PV stocks, while approximately 6 Mt reach end-of-life and become available for collection and recycling. These outcomes are contingent on a substantial scale-up of collection systems and policy enforcement and should therefore be interpreted as an upper-bound estimate rather than reflections of current regional capabilities. However, even under these ambitious conditions, only a little over half of these outflows are recoverable. It is projected that 2 Mt of materials embedded in end-of-life modules remain uncollected, and a further 1 Mt will be lost as processing residuals. Beyond uncollected materials and

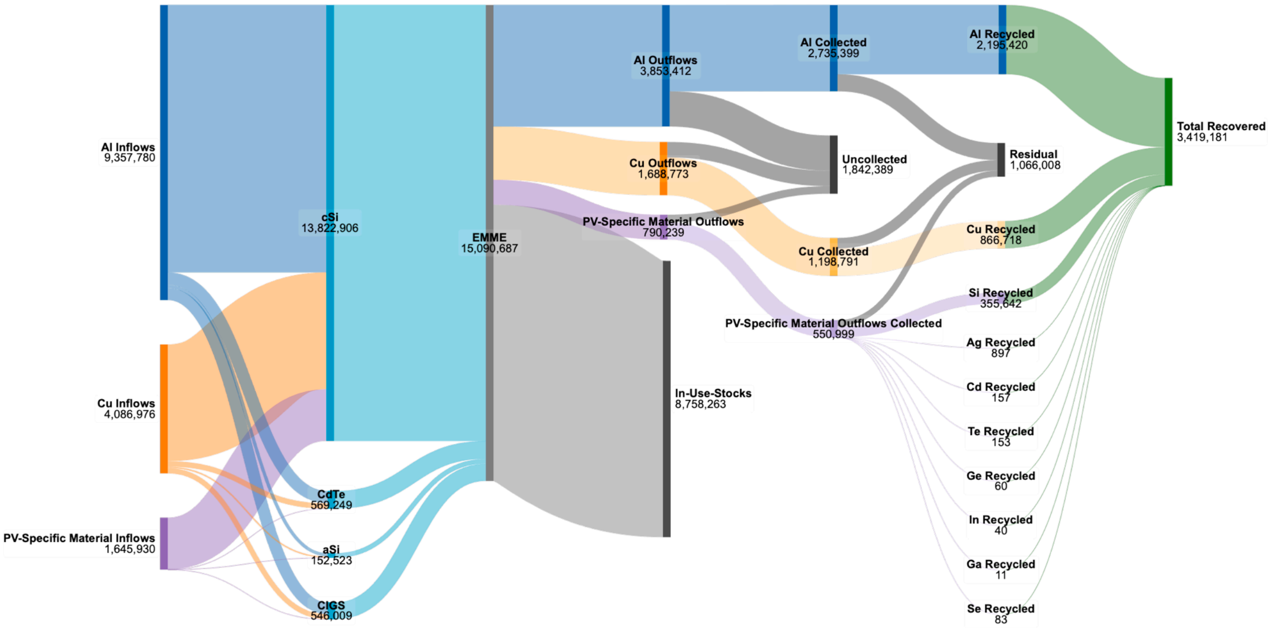

Fig. 6. Material flows for PV Systems in the EMME region under the high circularity scenario for the RTNZ pathway (cumulative flows from 2000 to 2055).

process-related losses during recycling, the limited recovery is also influenced by the underlying scenario assumptions. In particular, module lifetimes (22 years ± 5 years) delay the generation of end-of-life flows, while circularity performance improves only gradually over time, as collection rates and recycling efficiencies increase progressively rather than instantaneously. As a result, recovery remains constrained, particularly in earlier periods when both collection and recycling systems are still developing.

4. Discussion and policy implications

The EMME region exhibits substantial heterogeneity across the countries in terms of deployment, industrial capacity, income levels, and waste governance. Per capita material inflows range from very low levels in countries such as Syria to significant higher values in Greece, the UAE and Qatar. To interpret these differences, countries can be broadly grouped based on the interaction between structural characteristics and model outcomes (ST21) which in turn shapes material demand, circularity potential and exposure to supply risk across the region.

4.1. Spatial and temporal trends in material accumulation

The spatial concentration is primarily driven by high-deployment and industrialising systems. The UAE, Saudi Arabia, Iran, Egypt and Turkey are responsible for the majority of regional material stocks and future waste streams. The pronounced geographical imbalance in our results aligns with industry reports (MESIA, 2025), which show that these countries are expected to contribute nearly two-thirds of solar capacity additions in the coming decades. On the other hand, intermediate systems (e.g. Greece, Jordan, Oman) exhibit growing material demand without fully developed industrial or end-of-life management capacity which potentially increase the risk of future system imbalances. At the same time, smaller, import-dependent and less industrialized systems (e.g. Cyprus, Lebanon, Palestine) face a different challenge; despite their lower absolute material demand, limited domestic capacity and weak recycling infrastructure. Overall, these structural disparities lead to uneven exposure to both supply chain vulnerabilities and waste management challenges across the region. High-deployment countries, who are likely to face increasing pressure from concentrated material inflows and future waste streams are natural candidates for hosting regional recycling hubs. Distributed hubs which would link the Gulf (UAE or Saudi Arabia), North Africa (Egypt) and Eastern Mediterranean (Turkey) – could potentially curb transport distances and reduce transport costs which remain key barriers for PV recycling (Gentilini and Salt, 2020; Weckend et al., 2016). This would also avoid inefficient multiple investments in smaller facilities. Given the projected temporal dynamics of material flows, with end-of-life volumes increasing significantly towards the 2040s, timely development of regional coordination mechanism is essential to enable cross-border movement of PV waste in compliance with regulatory frameworks (i.e. Basel Convention and national requirements).

4.2. System turnover and first signs of circularity

Our results indicate that large-scale end-of-life outflows begin in the early 2040s and more spatially distributed and less intense deployment scenarios (i.e. RTNZ & UTNZ) lead to earlier crossover points (outflow>inflows). EMME region's timeline is not unique: outflows are projected to peak around 2040s in US (Ovaitt et al., 2022), from 2034 in China (Wang et al., 2025) and from 2036 in EU (Foster et al., 2025). PV-specific collection systems and Extended Producer Responsibility (EPR) Schemes should therefore be established well before 2040 so that institutional, financial and infrastructural arrangements are in place when the large-scale outflow wave arrives. The largest stockholders potentially could take the lead in piloting harmonized schemes that can be aligned with the logic of EU WEEE directive and Basel-convention e-waste controls setting collective PV-specific collection and recycling targets. Such strategies would offer predictable financing, internalize environmental costs, enable traceable material flows and allow cross-border movement of PV waste within the region (OECD, 2024).

4.3. Supply stress and fair share constraint

Our benchmarking of PV material demand against the EMME region's fair share of global supply, complemented by an economy-wide static assessment for PV-related materials in 2022, reveals a structurally import-dependent system for PV-related materials (World Trade Organization WTO, 2022). Within the PV system, germanium and tellurium emerge as the primary supply risk materials. When economy-wide demand is considered, supply stress extends to aluminium, copper, and silver. Turkey stands out as the only country exhibiting net export capacity in a critical material, specifically tellurium. In contrast, aluminium and copper are the only materials for which the region demonstrates broader export capacity, primarily driven by Gulf countries and Greece, with Turkey also contributing to copper exports. The remaining countries are net importers across most PV-related materials. Germanium, indium and silicon are classified as critical raw materials by the EU (European Commission, 2023), while germanium and tellurium are also identified in international assessments as by-products exhibiting low substitution potential and being subject to high supply concentration that limit the flexibility of their supply (IEA, 2025). These constraints are also observed at the country level, including major producing countries such as China (Dong et al., 2025), confirming that the high-risk materials identified in this study align with broader criticality concerns. Taken together, the combination of import dependence, concentrated supply risks, and limited regional processing capacity highlights the need for coordinated policy responses. In the Gulf region, for instance, supply risks may be further intensified by geopolitical uncertainties reinforcing the importance of the diversification strategies, regional cooperation and investment in domestic recycling and processing capacity. Most importantly, governments in the EMME region would benefit from national-level critical raw material (CRM) assessments alongside a consolidated regional list. Such coordinated assessments are a critical first step in identifying priority materials and informing circular economy strategies including evaluations of economic importance, supply risk, by-product dependence and substitution potential. This would also help frame circularity from a broader industrial and security context, raising its priority in national agendas and guiding sustainable procurement, regional trade planning and recycling innovation.

4.4. *Circularity potential – and what might be missed*

Material supply constraints are not unique to the EMME region but represent a global challenge that increases vulnerabilities in the green energy transition. Without circular economy strategies, these constraints may undermine the energy transition itself, as also observed for the US (Wang et al., 2022) and reflected in the EU's Circular Economy Action Plan, which calls for stronger secondary raw material markets (European Commission, 2020). However, circularity alone is not sufficient to overcome these constraints either; it must be complemented by coordinated deployment strategies, regional cooperation, and alignment between supply, demand, and end-of-life management systems. Our results show that, in the absence of a decarbonisation objective and regional cooperation, countries pursue independent, cost-optimised strategies that accelerate PV uptake and material inflows. In contrast, the RTNZ and UTNZ scenarios smooth the timing of investments and diversify them, hence easing pressure on PV supply chains. When combined with circularity results, our findings indicate that a gradually established collection and recycling system in the region could avoid a substantial share of projected primary material demand by 2050–2055. Under the HCS, approximately 70% of aluminium, 68% of copper, 88% of silicon, 73% of cadmium, 62% of tellurium, 63% of indium, 61% of gallium, and 65% of selenium needs can be met by the end-of-life outflows (ST20) with secondary supply even exceeding the projected primary demand for certain materials, including silver (196%) and germanium (129%). Notably, these estimates do not account for earlier circular strategies – such as repair, reuse, or repowering – which could further increase material recovery potential. Without strengthened regional coordination, however, these opportunities remain fragmented. Under the uncoordinated pathway, higher primary material demand persists, while limited integration of circular systems reduces the potential to recover and reintegrate materials into the economy. In such a context, material constraints may not only increase environmental pressures but could also limit the feasibility of large-scale PV deployment itself, with implications for both energy security and the sustainability of the global green energy transition.

Building on this finding, it is important to note that circular economy strategies are already being actively advanced in other regions. The EU, for instance, is strengthening its Circular Economy Action Plan and Waste Shipment Regulation to retain secondary raw materials within its borders, while also promoting broader enablers such as digital traceability, reuse pathways, and closed-loop material reintegration (Nyffenegger et al., 2024). For the EMME region, this evolving landscape underscores both a risk and an opportunity. Without timely action, the region risks falling further behind in accessing secondary material streams. At the same time, developing efficient collection, recycling, and traceability systems could position EMME countries to engage in joint ventures, technology transfer, and integrated value chains with the EU—particularly through existing institutional links (e.g., Cyprus and Greece), association agreements (e.g., Egypt), and customs union arrangements (e.g., Turkey).

5. Limitations

This study provides a first-order assessment of PV material dynamics in the EMME region; however, several limitations should be noted. First, the dynamic MFA framework is based on exogenously defined deployment scenarios and does not incorporate feedback mechanisms such as price dynamics, supply constraints or material substitution. As such, the results should be interpreted as indicative of deployment-driven material demand and associated supply pressures, rather than market-adjusted outcomes. Second, earlier circularity strategies, such as repair, reuse, or repowering – are not included in this study and the analysis does not account for material quality or the functional substitutability of recycled outputs. Third, key assumptions including material intensity trajectories and an average system lifetime of 22 ± 5 years introduce uncertainty particularly under evolving technological and environmental conditions. Fourth, the GDP-based fair share approach provides an indicative measure of supply pressure but does not capture the full complexity of criticality, including geopolitical, economic, and technological factors. Finally, the system boundary does not account for cross-sectoral material demand from other technologies, which may increase overall supply pressure.

6. Sensitivity analysis

A sensitivity analysis was conducted to assess the robustness of key assumptions, including material intensity trajectories, module lifetimes (15–30 years), the effect of module life-time on circularity outcomes (LCS/HCS), price variability (±30%) for selected materials, and alternative fair-share allocation principles (GDP- vs population-based). Detailed results are provided in the SI.

7. Conclusion

This paper presented a regional assessment of PV material requirements in the Eastern Mediterranean and Middle East (EMME), integrating a dynamic, retrospective and prospective Material Flow Analysis with indicative supply risk and circularity assessments. It shows how alternative energy transition pathways shape the scale, distribution, and supply pressure of PV-related material flows, as well as their circularity potential. Three main insights stand out.

First, coordinated net-zero pathways with regional energy trade can substantially lower material requirements and ease pressure on the primary global supply. Compared to a nationally fragmented transition, cumulative PV-related material accumulation is lower by nearly one third, while earlier crossover points enable earlier opportunities for secondary material recovery.

Second, supply risk remains structurally concentrated in germanium and tellurium. These materials consistently emerged as high-risk materials regardless of the energy transition pathway. Silicon, aluminium, and copper approach moderate risk levels. A static 2022 analysis further indicates that broader economy-wide demand for aluminium, copper, silver, and germanium already places pressure on global supply and points to systemic vulnerabilities beyond the PV sector.

Third, the circularity analysis of this paper showed that effective collection and recycling strategies could transform germanium from a high-risk to a potentially surplus material under improved system conditions. Moreover, primary demand can potentially be reduced for several other materials too - including >70% for aluminium, about 88% for silicon, and in the case of silver, potentially exceeding 100%, noting that these estimates do not account for earlier circularity strategies (e.g., repair, reuse, or repowering) or material quality constraints.

Taken together, these findings underscore that material requirements, supply security, and circularity are not peripheral considerations, but fundamental to the EMME region's energy transition, particularly if its exceptional solar potential is to be realised in a socially, economically, and environmentally sustainable manner. Developing a resilient and competitive PV sector will require strategic foresight, regional cooperation, and targeted investment. In this context, the advancement of circular economy strategies, the development of shared infrastructure, and the alignment of policy frameworks can play a pivotal role in enabling sustainable production–consumption systems across the region.

CRediT authorship contribution statement

Ulku Tasseven: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Theodoros Zachariadis:** Writing – review & editing, Validation, Supervision, Conceptualization. **Constantinos Taliotis:** Writing – review & editing, Data curation. **Qiyu Liu:** Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2026.108999.

Data availability

The data supporting the findings of this study are available in the Supplementary Information provided with this article.

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