

Thermodynamic-based perspectives on critical raw materials in photovoltaic energy production: the Italian case

Giulia Grisolia*

*Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy (giulia.grisolia@polito.it)

INTRODUCTION & AIM

Global decarbonization efforts have accelerated the deployment of renewable infrastructures, particularly photovoltaic (PV) systems. However, this transition increases the demand for Critical Raw Materials (CRMs), involving energy- and carbon-intensive extraction and refining processes [1]. While traditional criticality assessments focus on mass-based demand or supply risks, they frequently overlook the physical quality of resources and the irreversibility of their transformation; e.g., high-purity refining, essential for solar-grade silicon, entails substantial exergy inputs that reflect the effort to overcome resource degradation.

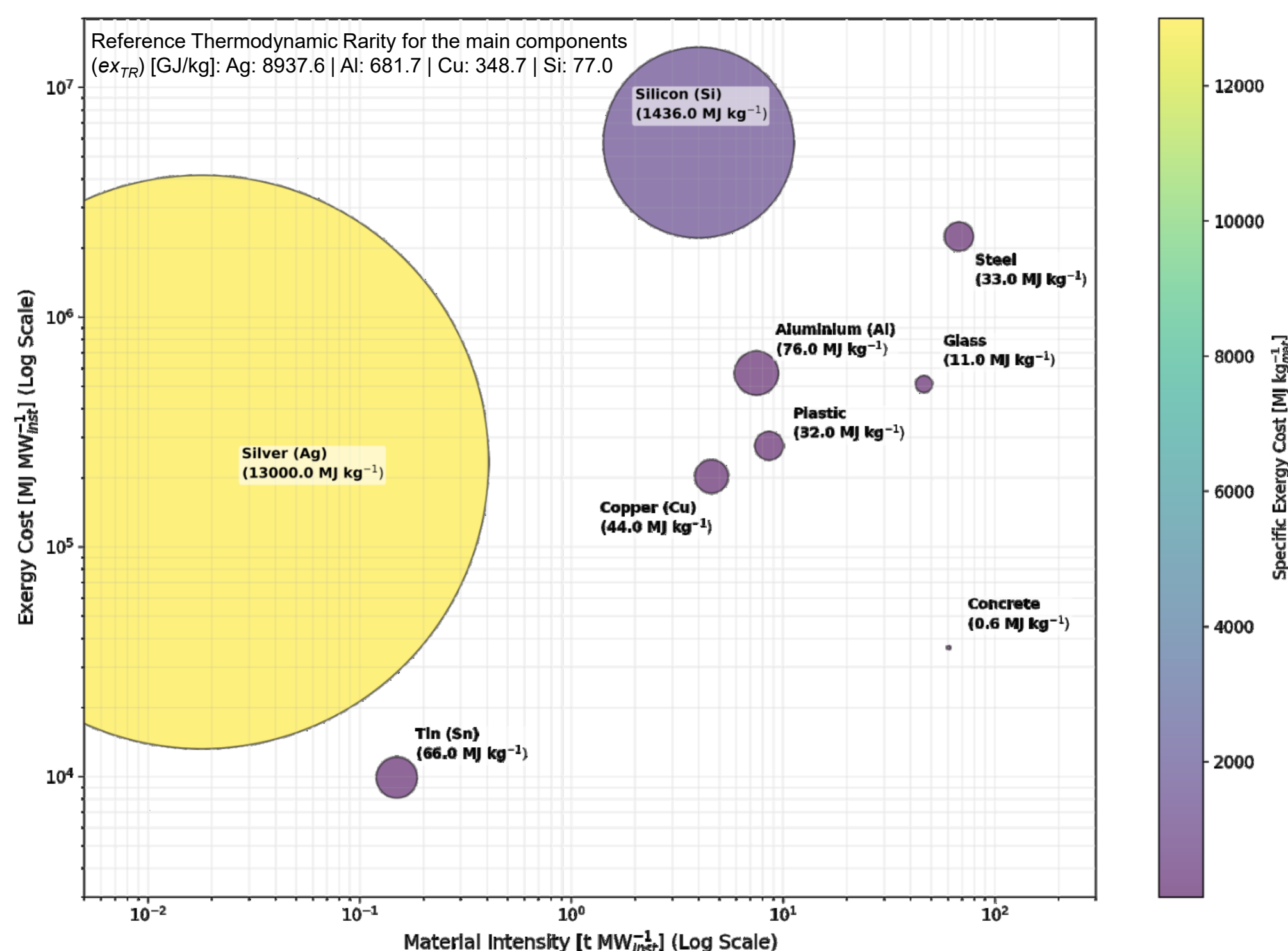
This study applies the Exergy Costing framework to the Italian National Energy and Climate Plan (PNIEC) 2030 scenario [2]. By integrating material-specific exergy intensities with national deployment projections (including the repowering over time), the analysis quantifies the cumulative exergy requirements inherent in the technological transition to explore how exergy-based metrics can provide a physics-based characterisation of resource quality, offering an additional layer of information to established environmental and socio-economic indicators. Integrating this approach in a broader framework can support a more comprehensive evaluation of the long-term sustainability and resource efficiency of material-intensive energy technologies.

METHODOLOGICAL FRAMEWORK

- Technology characterisation:** crystalline silicon (c-Si) PV panels have been considered (~97% Italian market share), with their average (assumed constant in the time-frame under analysis) material intensities [$t_{mat}/MW_{ins,t}$] from Ref. [1], and their specific exergy costs [$MJ/kg_{mat,t}$], covering: mineral, mining and concentration (M&C), smelting and refining (S&R) stages for the material-grade required by the technology, data derived from Ref. [3]. **Fig. 1** and **Fig. 2** capture the material's technological exergetic profile.
- Inventory analysis:** the focus is on the key components in terms of materials constituting c-Si PV technologies: Silicon (Si PV-grade), Aluminium (Al), Copper (Cu), Silver (Ag), Tin (Sn), Steel, and Concrete.
- National Scenario:** Cumulative and annual deployment targets are based on the Italian PNIEC 2030 (target₂₀₃₀: 79.3 GW total operational capacity) [2].
- System Dynamics (Repowering):** Total annual material demand was calculated by integrating net capacity growth with the replacement of end-of-life assets, assuming a 20-year operational lifetime.
- Thermodynamic Metrics:** The analysis employs the *exergy cost* as a proxy for the total physical effort of manufacturing (total exergy required for material manufacturing), and the Thermodynamic Rarity (ex_{TR}) metric [4] used to assess resource quality by accounting for both the technological effort (*exergy cost*) and the Exergy Replacement Cost; the latter estimates the natural exergy required to reconcentrate minerals from a degraded state (common rock) to the current ore grade, providing a physical measure of resource rarity.

Fig. 1: Exergy Cost vs. Material Intensity for materials in c-Si PV modules. Bubble size represents specific exergy intensity (per mass unit), data derived from [1,3].

Material Map: Material Intensity vs. Exergy Cost in PV panels



FUTURE WORK / REFERENCES

- [1] European Commission, JRC. *Harmonised rules for the calculation of the CF of PV modules in the context of the EU Ecodesign Directive*. Luxembourg: Publications Office of the European Union; 2025
- [2] MASE. *Integrated National Energy and Climate Plan 2021-2030, 2024 Update (PNIEC)*; Italian Republic: Rome, Italy, 2024.
- [3] Torrubia, J.; Valero, A.; Valero, A. Renewable exergy return on investment (REXROI) in energy systems. The case of silicon photovoltaic panels 2024, *Energy*, **304**, 131961. DOI: 10.1016/j.energy.2024.131961
- [4] Iglesias-Émbil et al. Raw material use in a battery electric car - a thermodynamic rarity assessment. *Resources, Conservation & Recycling* **2020**, *158*, 104820. DOI: 10.1016/j.resconrec.2020.104820

RESULTS & DISCUSSION

The analysis of the Italian PNIEC 2030 scenario, based on the *Exergy Cost* of materials, quantifies the total exergetic requirement for the national PV deployment. The cumulative exergy cost for the 2021-2030 decade reaches ~700 PJ (**Fig. 3**). The results show that by 2030, the *Exergy Cost* associated with infrastructure repowering will account for 22.5% of the total annual exergy cost, highlighting the impact of asset replacement on the physical requirements of the transition.

The integrated assessment of the Italian PV fleet (2021-2030) shows a cumulative exergy output/cost ratio of 2.70 at 2030. This value characterises the performance of the national fleet during the analysed timeframe. While Silicon represents the highest exergy cost per MW due to its high material intensity and the chemical/electrical effort required for its purification, materials like Silver show a significantly higher *Thermodynamic Rarity*, indicating a superior exergetic geological rarity, which makes them critical despite their low mass share.

Moreover, the high Exergy Cost of functional materials (including Silicon, Aluminium and Copper) is directly related to the technology's Carbon Intensity (kg_{CO_2}/kWh). Since their exergy cost is dominated by electricity and fossil-related inputs - including chemicals - in the smelting and refining stages (as shown in **Fig. 2**), the associated GHG emissions depend on the energy mix of the manufacturing phase. These findings suggest that long-term sustainability requires a focus, among others, on renewables used in the material production chain, material intensity, and the extension of technology lifetime to mitigate the cumulative exergy cost of the transition.

Italy (2021-2030 analysis): Cumulative Material Exergy Cost vs. Energy Delivered - PV systems

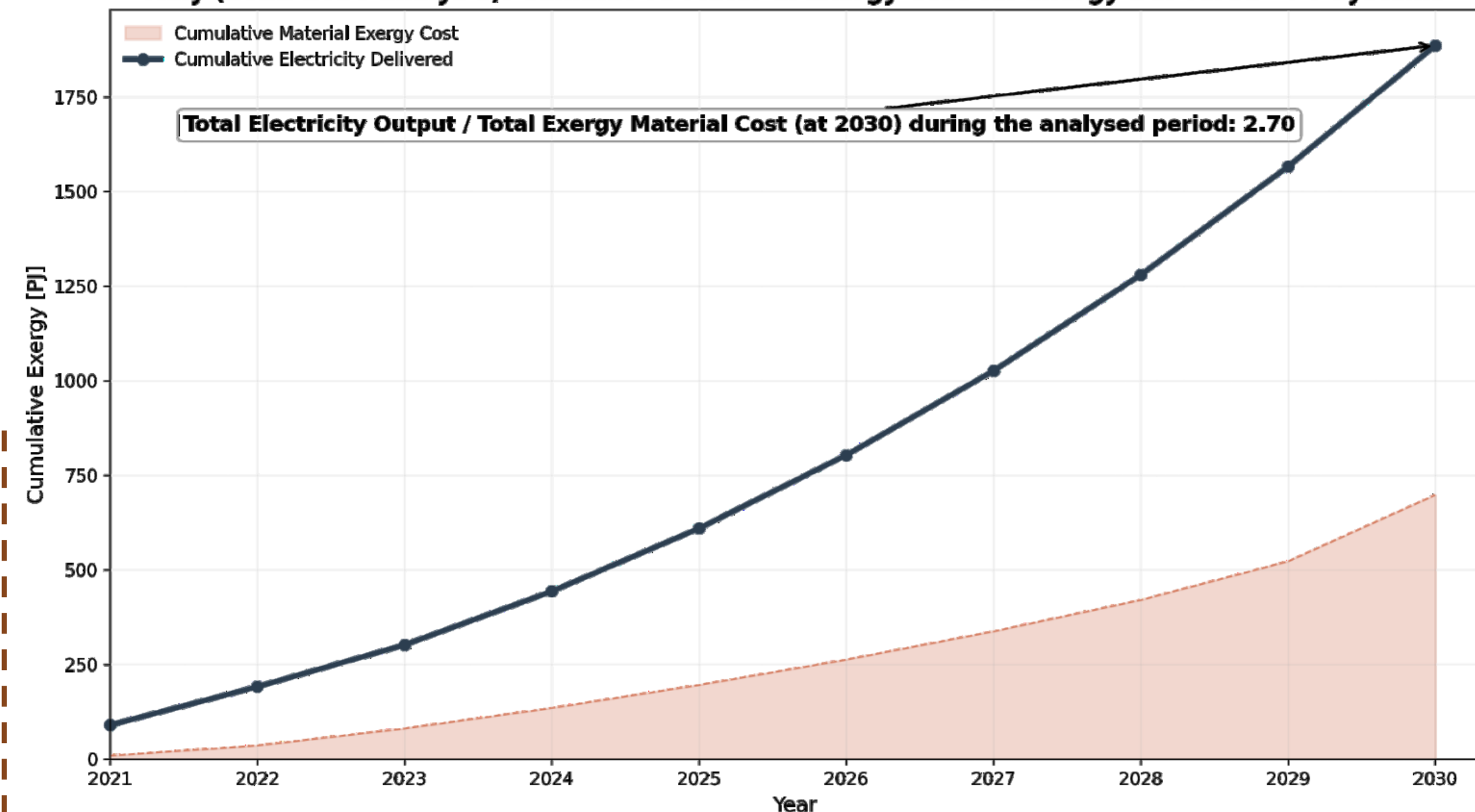


Fig. 3: Cumulative exergetic assessment IT-PV fleet (2021-2030). The chart compares the integrated exergy cost of materials (including repowering) with the integrated exergy output (electricity delivered). The 2030 ratio characterises the system's exergetic performance during the (2021-2030) PNIEC transition

Exergy Cost Breakdown per PV-grade material

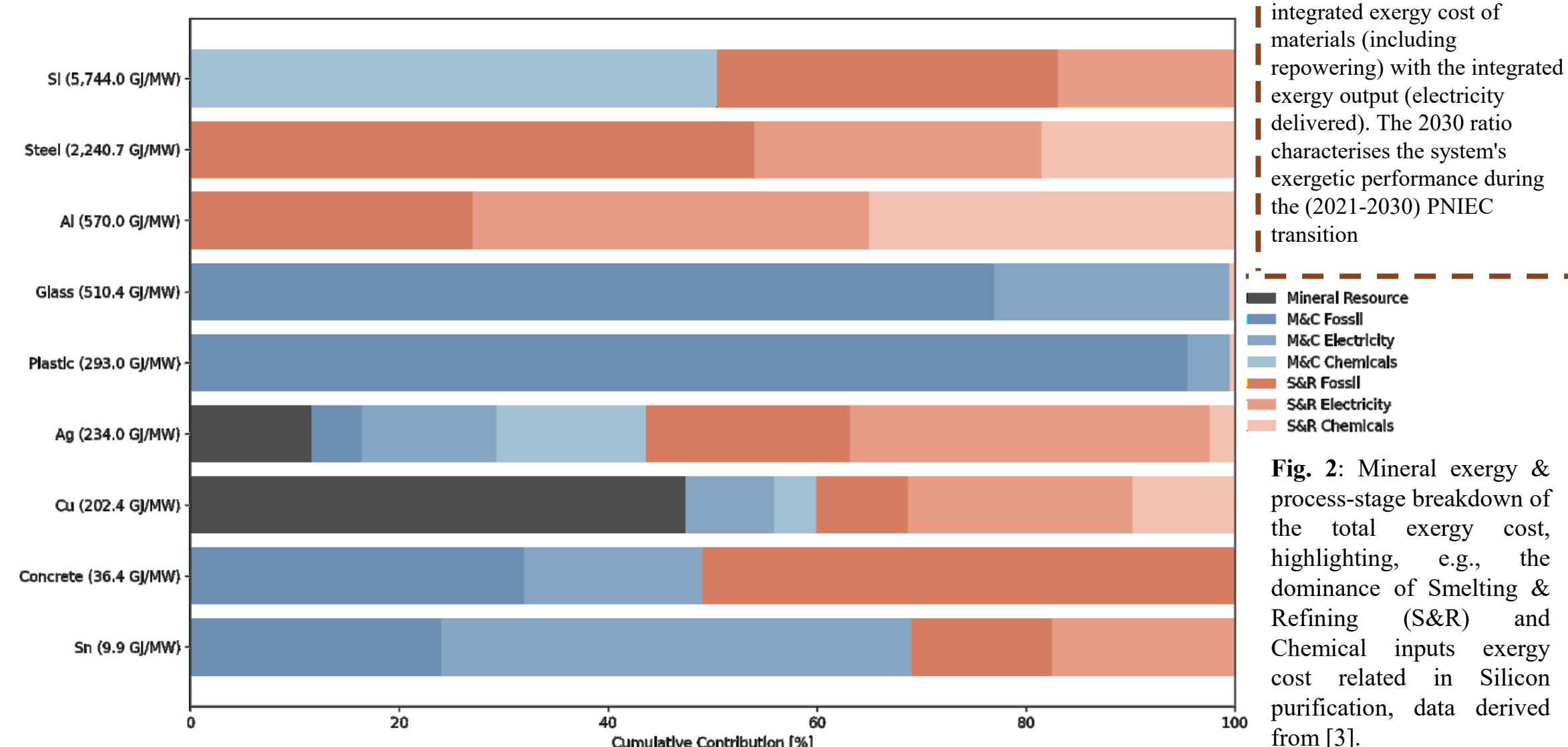


Fig. 2: Mineral exergy & process-stage breakdown of the total exergy cost, highlighting, e.g., the dominance of Smelting & Refining (S&R) and Chemical inputs exergy cost related in Silicon purification, data derived from [3].

CONCLUSION

- Complementary Metrics:** traditional energy/environmental indicators can be effectively supported by exergy costs and ex_{TR} , providing a physical characterisation of resource quality and the effort required for high-purity technological refining.
- The PNIEC scenario:** the transition requires a significant exergy investment, ~700 PJ for the 2021-2030. By 2030, the annual exergetic effort for infrastructure repowering will reach ~22% of the total, thus a growing share of resources must be dedicated to maintaining the existing fleet.
- Long-term Sustainability:** The cumulative output/cost ratio of 2.70 characterises the system as a "net exergy producer" within 2021-2030. However, the rising demand for both new installations and repowering suggests that extending technology lifetime and improving material circularity are undoubtedly key strategies to manage the exergetic requirements of the long-term energy transition.