MATERIAL FEASIBILITY OF EUROPEAN ENERGY SYSTEM MODELS

Jan MUTKE[1]*, Jonas FINKE[2], Katharina ESSER[2], Heidi HEINRICHS[1,3]

The large-scale integration of renewable energies and flexibility options such as batteries or electrolyzes is crucial to decarbonize the European energy system. While these technologies can reduce dependence on imported energy carriers, they require significantly more critical raw materials than conventional generation [1]. As the production of these materials is geographically concentrated, governments increasingly monitor the criticality and develop resource strategies to secure national supply [2,3]. In this context, energy system models play an important role in informing such strategies by quantifying future capacity requirements. Yet, most models do not account for the material demand linked to their proposed infrastructures, potentially overlooking constraints that could challenge the physical feasibility of the resulting systems [4]. To address this gap, we conduct a literature review of European energy scenarios based on energy system models and perform an ex-post assessment of the material feasibility of the future systems they describe.

Methodology

We conduct a literature review to identify a broad spectrum of scenarios that propose highly decarbonized European energy systems. From all eligible studies, we extract the reported capacity expansions if they are specified. Because the technological detail in these models is often heterogeneous and available data on material intensities is limited, we focus on major technologies and thus represent a lower bound of material requirements; technologies not considered make our estimates conservative. As many studies do not specify technology sub-types, but they differ in their material intensities, we apply future market share roadmaps for sub-technologies to the extracted capacity expansions. To assess the material feasibility of each system, we calculate material-demand-to-reserve ratios for all relevant materials. The evaluation is performed by combining capacity expansions with multiple material-intensity scenarios and comparing the resulting material requirements to the reserves accessible to the EU, measured relative to (a) population and (b) economic size.

Results

Preliminary results indicate that the material requirements of several proposed European energy scenarios exceed the reserves accessible to the EU. This is more pronounced under the population-based allocation, but material shortages also occur when using the economic allocation. Notably, tellurium emerges as a limiting material for photovoltaic generation, while dysprosium poses constraints for offshore wind generation. Our insights help to identify where technology choices or deployment pathways could lead to material bottlenecks that need to be addressed through alternative sub-technology development, improved recycling efforts or require an increased focus on supply chain strategies.

[1] Institute of Climate and Energy Systems – Jülich Systems Analysis, Forschungszentrum Jülich, Wilhelm-Johnen-Straße, 52428 Jülich, Germany, +49 2461/61-9381, j.mutke@fz-juelich.de
[2] Chair of Energy Systems and Energy Economics, Ruhr Universität Bochum
[3] University of Siegen, Department of Mechanical Engineering, Chair for Energy Systems Analysis, Siegen, Germany

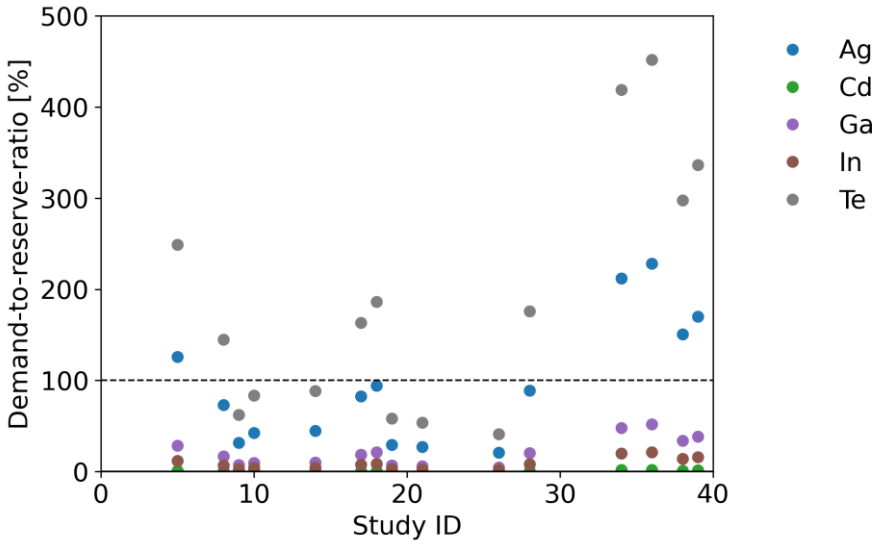

Figure 1: Excerpt from the preliminary results showing the material demand to reserve ratio for Photovoltaic capacity expansion. Here, the reserve estimates are based on a population-weighted allocation for the EU. Entries are omitted where no expansion data were available.

References

[1] International Energy Agency (2021). *The Role of Critical Minerals in Clean Energy Transitions*. IEA, Paris. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions (accessed 24.11.25)

[2] G. Mudd, P. Josso, R. Shaw et al. (2024). *UK 2024 Criticality Assessment (OR/24/047)*. UK Critical Minerals Intelligence Centre / British Geological Survey. https://www.ukcmic.org/downloads/reports/ukcmic-2024-criticality-assessment.pdf (accessed 24.11.25)

[3] European Union (2024). *Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework to ensure a secure and sustainable supply of critical raw materials (Critical Raw Materials Act)*. Official Journal of the European Union, L 202, pp. 1–57. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R1252 (accessed 24.11.25)

[4] G. Colucci, J. Finke, V. Bertsch et. al. (2025). *Combined assessment of material and energy supply risks in the energy transition: A multi-objective energy system optimization approach.* Applied Energy, 388, 125647, https://doi.org/10.1016/j.apenergy.2025.125647