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Preview

From fossil fuels to metals and minerals: Navigating global resource challenges in the energy transition

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Renewable energy systems introduce an unprecedented rise in demand for multiple raw materials. In a recent *Cell Reports Sustainability* article, Qiu et al. show the need for huge increases in the supply of twelve key materials for the power sector by 2050. Here, we broaden the perspective to ultimately derive solutions to successfully navigate material bottlenecks of the energy transition.

The global energy supply has always relied on vast quantities of raw materials. In the past decades, these have mainly consisted of hydrocarbons such as coal, oil, and gas. But with the rise of renewable energy sources such as wind and solar, the reliance on these energy resources may be replaced by an increasing demand for metals and minerals. Although the nature of the resource demand may be changing, many of the challenges associated with their supply remain largely the same (see Figure 1). While fuel supply challenges have been studied for decades, driven by concerns about peak oil and events such as the oil crisis, research on the energy-material nexus and the material crisis has only gained substantial attention in recent years.[1]

Understanding the systemic challenge

It may appear that the reduction of coal-fired electricity generation facilitates the decoupling of commodities from energy supply. In fact, the opposite is true: the greater the deployment of renewable energy technologies, the more integrated the energy and material economies become.

In this context, a recent *Cell Reports Sustainability* article by Qiu et al.[2] extends the open-source integrated assessment model GCAM (Global Change Analysis Model) to endogenously identify demands for 12 key materials arising from the transformation of the global power sector and the influences of potential supply shortages on the sector.

Their findings demonstrate that if the supply of these 12 materials continues to expand at the same rate over the next 30 years as in the past, the development of the global electricity sector will be severely impeded. This leads to decreasing investments in the power sector and an increase in electricity prices worldwide. By analyzing a variety of exploratory scenarios, the authors are able to estimate the impacts of different growth rates for each of the 12 materials. While the restriction of materials utilized in numerous technologies, such as copper, results in a net reduction in installed capacity, the limitation of materials employed in specific (sub-)technologies, including neodymium, silicon, and graphite, gives rise to technological substitution.

The authors conclude that if an increase of the historical growth rates by a factor of 3 to 4 would be realizable, developments within the power sector by 2050 would remain largely unaffected. However, this increase would still be insufficient to supply the materials needed for the large capacity additions in the near term, resulting in a slower rate of electrification and an increased use of fossil fuels in some sectors.

To avoid such developments, Qiu et al.[2] highlight the importance of recycling and the reduction of material intensities, but they also discuss the expansion of primary supplies. Furthermore, the authors underscore the importance of conducting model-based analyses of the energy-material nexus, a recommendation that aligns with the findings of other studies on the integration of raw materials in energy system modeling.[1]

Addressing supply challenges

Supply shortages can be addressed by either increasing supply or reducing demand. A reduction in demand can be achieved through lowering the resource intensity of technologies and by substituting technologies or materials for which extreme shortages are expected. An increase in supply can originate from either primary resources, such as new mining capacities, or from secondary resources obtained through recycling. To realize the potential of these options in limiting material bottlenecks, it is essential to ensure their economic viability over a sufficiently long payback period. However, this argument is not adequately represented in current discussions.

Substitution and demand reduction

Substituting one technology with another that provides the same or a similar supply task but uses less-scarce materials poses one solution to reducing material bottlenecks. For some platinum-group metals, substitution and technology shifts are already seen, with one notable example of replacing iridium with platinum in crucibles.[3] However, a direct substitution is not always possible, and additional measures are often needed to achieve the same supply task. For example, switching from proton exchange membrane to anion exchange membrane water electrolysis reduces the demand for platinum and iridium,

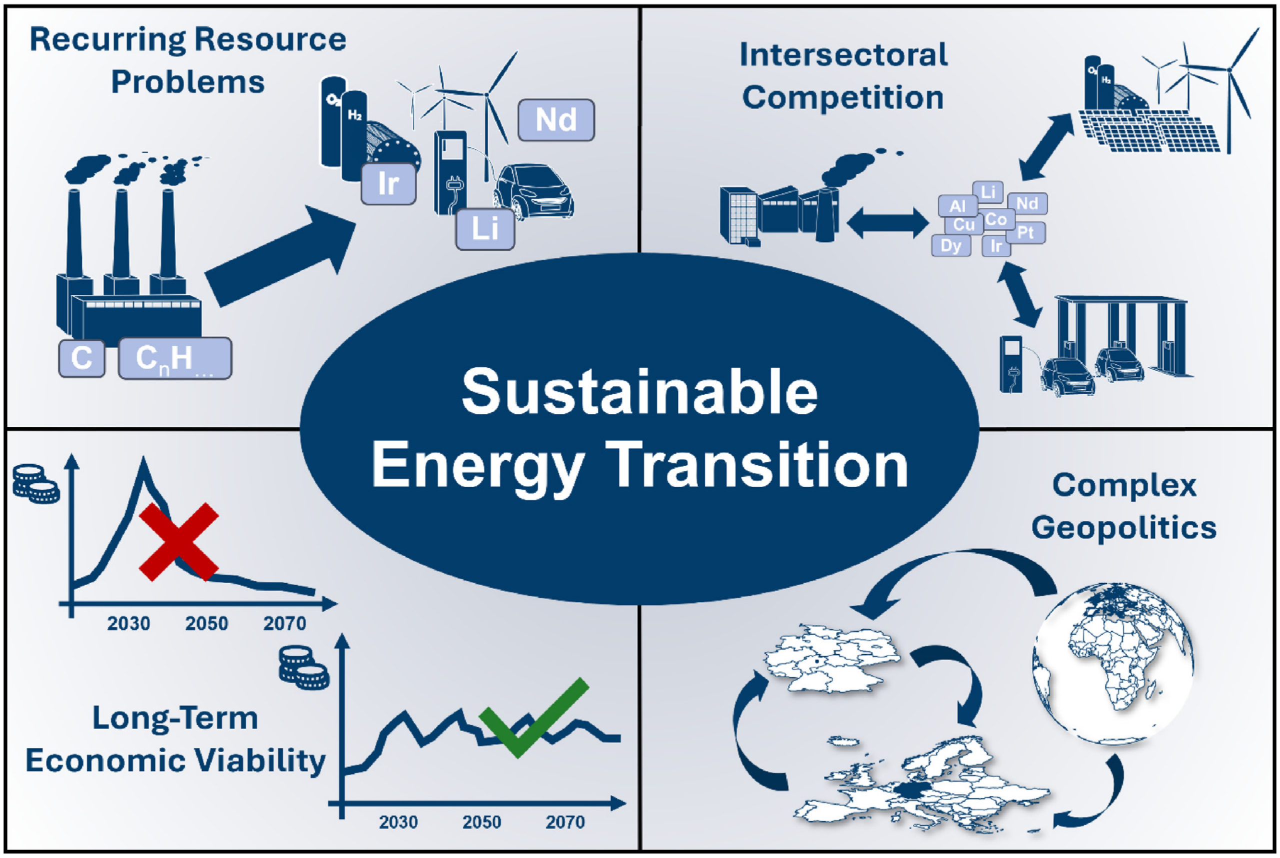

Figure 1. An illustration of the resource-related challenges that could affect a sustainable energy transition

but because both technologies feature different operational dynamics,[4] one cannot directly substitute the other. Each of these substitution cases requires detailed technical knowledge of its techno-economic and material characteristics in order to correctly assess its role in future energy systems. This level of detail has not been reached yet in model-based studies also due to the underlying data and computational challenges. Hence, it is likely that possible substitution options still remain unrevealed.

While substitution primarily affects the demand for raw materials by shifting it from one material to another, improving material efficiency could lead to a reduction in demand. The same applies to the exploration of methods for extending the lifespan of existing technologies, as opposed to the construction of new capacities.

Intersectoral competition and primary supply increase

Given that numerous studies focus exclusively on the energy sector,[1] competition for material supplies with other sectors is frequently overlooked. The scenarios proposed by Qiu et al.[2] indicate that the demand for certain materials from the power sector alone may exceed the current global supply. This emphasizes the importance of a comprehensive examination of other sectors, as simultaneous developments in these sectors could necessitate an increase in the supply of primary resources. However, this would inevitably necessitate additional mining activities, which pose multiple challenges. This process is not only cost but also time intensive, with an estimated 16-year timeline from initial exploration to the start of extraction.[5] Furthermore, the viability of new mines is contingent upon anticipated market developments, which can extend the timeline if investors await a rise in material prices before committing to new mining projects. In addition to the economic challenges, mining often has significant environmental and social impacts that need to be taken into account if future projects are to be realized in a sustainable manner.[6] An alternative to new mines might be the reuse of existing mine waste in the form of spoil heaps. This is because mine waste often still contains valuable raw materials.[7] However, it is not yet clear whether this is economically viable due to the low material concentration and whether the public will accept the reopening of mining sites in regions previously affected by potentially negative mining impacts.

Secondary supply increase

In addition to mining capacities, the utilization of secondary sources can mitigate the risk of supply bottlenecks. Furthermore, from a macroeconomic perspective, the inclusion of cost-effective recycling in energy systems could reduce the transformation cost by over 20%.[8] However, the recycling process is not without its own inherent challenges. First, the inconsistency of input streams of technologies, coupled with the fact that both long- and short-term profitability is contingent upon current resource prices, renders the formulation of optimal business cases for individual recycling processes a challenging endeavor. In addition, recycling does not provide a solution for near-term supply shortages. Many technologies that contain high amounts of precious metals and rare earth elements are still in use and remain far away from reaching their end of lifetimes.[7] As recycling also saves energy compared to primary production,[8] efforts should be made to maximize recycling rates. These efforts can include the implementation of mandatory recycling rates for certain materials, the development of recycling infrastructure, and the incorporation of recycling-friendly product design.

Toward a sustainable security of supply

In the same way that the Industrial Revolution started the era of carbon-based resources, the clean energy transition has initiated the era of critical raw materials. Many lessons can be learned from centuries of mining and burning fossil fuels—especially when it comes to security of supply.

In the past, some countries with high amounts of fossil resources such as Venezuela have not been able to benefit from their resource wealth but instead became economically and politically unstable, endangering security of supply in the long run, which is known as the resource curse—whereas others such as Norway have profited from its fossil resources. In the realm of critical materials for renewable energy technologies, a substantial share is extracted in countries where such mining represents a significant portion of the country's overall revenue, making them particularly susceptible to the resource curse.[5] Additionally, mining and processing of critical materials is often concentrated in only a few countries, which can lead to high import dependencies and security of supply threats around the world, similar to fossil fuel markets. Hence, from the perspective of sustainable security of supply, it is of utmost importance to balance a fair share of value added with security of supply for all.[9] The first might be facilitated by the establishment of production capacities for higher-value products in various resource-rich countries[9] to increase local economic growth and to allow for diversification of supply and, therefore, increasing security of supply for all. Locating recycling facilities in resource-poor countries might even further reduce issues of import dependencies and finally might reduce geopolitical tensions. In this manifold and highly complex field, model-based analyses such as those by Qiu et al.[2] need to and will find solutions to global resource challenges in the future.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Schulze, K., Kullmann, F., Weinand, J.M., and Stolten, D. (2024). Overcoming the challenges of assessing the global raw material demand of future energy systems. Joule *8*, 1936–1957.
2. Qiu, Y., Iyer, G., Graham, N., Binsted, M., Wise, M., Patel, P., and Yarlagadda, B. (2024). The impacts of material supply availability on a transitioning electric power sector. Cell Reports Sustainability *1*, 100221.
3. Cowley, A.P.G.M. (2023). Market Report (Johnson Matthey). 2023 May.
4. Martinez Lopez, V.A., Ziar, H., Haverkort, J.W., Zeman, M., and Isabella, O. (2023). Dynamic operation of water electrolyzers: A review for applications in photovoltaic systems integration. Renew. Sustain. Energy Rev. *182*, 113407.
5. The Role of Critical Minerals in Clean Energy Transitions (2022) (Paris: International Energy Agency).
6. Weinand, J.M., Vandenberg, G., Risch, S., Behrens, J., Pflugradt, N., Linßen, J., and Stolten, D. (2023). Low-carbon lithium extraction makes deep geothermal plants cost-competitive in future energy systems. Advances in Applied Energy *11*, 100148.
7. Geng, Y., Sarkis, J., and Bleischwitz, R. (2023). How to build a circular economy for rare-earth elements. Nature *619*, 248–251.
8. Kullmann, F., Markewitz, P., Kotzur, L., and Stolten, D. (2022). The value of recycling for low-carbon energy systems - A case study of Germany's energy transition. Energy *256*, 124660.
9. (2023). The global fight for critical minerals is costly and damaging. Nature *619*, 436.