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Commentary

Energy transition will require substantially less mining than the current fossil system

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René Kleijn is a professor of resilient resource supply at Leiden University in the Netherlands. He serves as the department head of the industrial ecology group at Leiden University and the scientific lead of the Circular Industries Hub at the Leiden-Delft-Erasmus Centre for Sustainability. His research primarily centers on sustainability matters, employing quantitative methods like life cycle assessment and substance and material flow analysis. Kleijn's expertise extends across various industries, including chemicals, energy, and recycling, where he effectively applies these methodologies to address environmental challenges. He has actively participated in numerous large consortia as part of EU-funded research projects. In recent

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years, his research has focused on critical raw materials, resilient supply chains, circularity, and material constraints within the evolving landscape of the energy transition.

Excavation worries

The International Energy Agency (IEA) estimates a 6-fold increase of energy transition-related mineral demand between 2020 and 2040 in their 2050 net-zero emissions (NZE) pathway.[1] Both the availability of these minerals and the considerable environmental and social impacts related to mining, from biodiversity loss to human rights violations, are raising concerns among policy makers and the public.[2,3] Some of the consequences of mineral demand for the energy transition have been addressed in prior research,[1,3–5] but a comparison against current mining activities for the fossil-fuel-dominated energy system has not been made.

It is not possible to draw conclusions about the mining-related impacts of the energy transition based solely on mineral demand, because very different mining activities are required for each mineral.[1,5] This requires a translation of material demand to mineral ore extraction based on factors such as ore grade, mineralogy, depth, and mine location.[5] Ore grade is the most influential, explaining 68.9% of the extraction differences for 25 minerals in a previous study.[5] Ore grade also largely determines the amount of water and energy used, the volume of process reagents required, and land disturbed and is subject to mineral-specific and uncertain ore grade declines.[6,7]

The comparison between energy transition-related mining and fossil fuel extraction is further complicated by conceptual differences. While the refinement of mined coal (known as run-of-mine) into production-ready coal and the refinement of minerals from ore are similar, there is a significant difference when we consider the dissipative nature of fossil fuels compared to the stocks of materials that persist for a longer time in the technologies of the energy transition.[2] This means that the high demand for minerals through the energy transition is of a (temporary) stock building nature, while fossil-related extraction is continuous and dissipative. In the longer term, the decommissioning of end-of-life renewable generation provides opportunities for reuse or recycling. This can mitigate demand of primary produced minerals for new renewable installations.[1,8]

We show that, while new mining developments (in general) can have significant environmental consequences,[1,3,6,7] the concern that the energy transition will require a large expansion in overall, global mining activity compared to today's energy system is unfounded. This is true both in the long-term and, crucially, also during the build-up phase of the energy transition.

We assess the scale of mining activities during the energy transition by calculating mining activities based on three factors: (1) annual mineral and coal demand calculated from capacity additions and coal production according to the IEA NZE scenario (the scenario with the highest assumed mineral demand for energy transition technologies),[1] (2) ore grades that translate material demand into mineral extraction and for coal extraction ratios for run-of-mine coal to production-ready-coal (focusing on mining volumes specifically instead of the whole mining and refining process), and (3) current recycling rates to quantify secondary production of minerals (see the overview in the supplemental information section 1.14).

We also consider the effect of a substantial improvement in recycling and the potential for uncertain ore-grade decline. We excluded byproduct minerals to avoid double counting. We used a high-resolution model for estimating the minerals required for core technologies, solar photovoltaic (PV), wind power, and on-road (electric vehicle; EV) battery capacity, since these represent the majority of material demand for energy transition technologies described in the NZE scenario.[1,9] We also estimated the ore extraction of additional energy transition technologies and electricity network additions (other technologies and infrastructure). The recycling scenario "current recycling" assumes static recycling rates until 2050, and "substantial improvements in recycling" assumes a steady increase of conventional and technology-specific recycling rates until 2040 to indicate the range of potential of recycling improvement (for data and methods, please see the supplemental information section 1).

Extraction for coal compared to energy transition minerals

Our results show that coal continues to dominate ore extraction for the overall NZE scenario energy system until the early 2030s, after which demand for core technologies solar PV, wind power, on-road battery, and other energy transition technologies overtake coal (see Figure 1A). In this NZE scenario, coal production declines from 97% of total ore extraction to 22% by 2050, while capacity additions for core technologies increase sharply before reaching a peak in 2045 (see Figure S5A in the supplemental information). However, the total mass of ore extraction for core technologies over time experiences a large decrease compared to a continuation of current coal production. Ore extraction is largest for EVs, growing 55 times from 2021, compared to 13 and 9 times for solar PV and wind power, respectively. Over time, EV battery production significantly increases in its share of the overall core technology extractions, from 44% to 87%. Ore extractions can be significantly

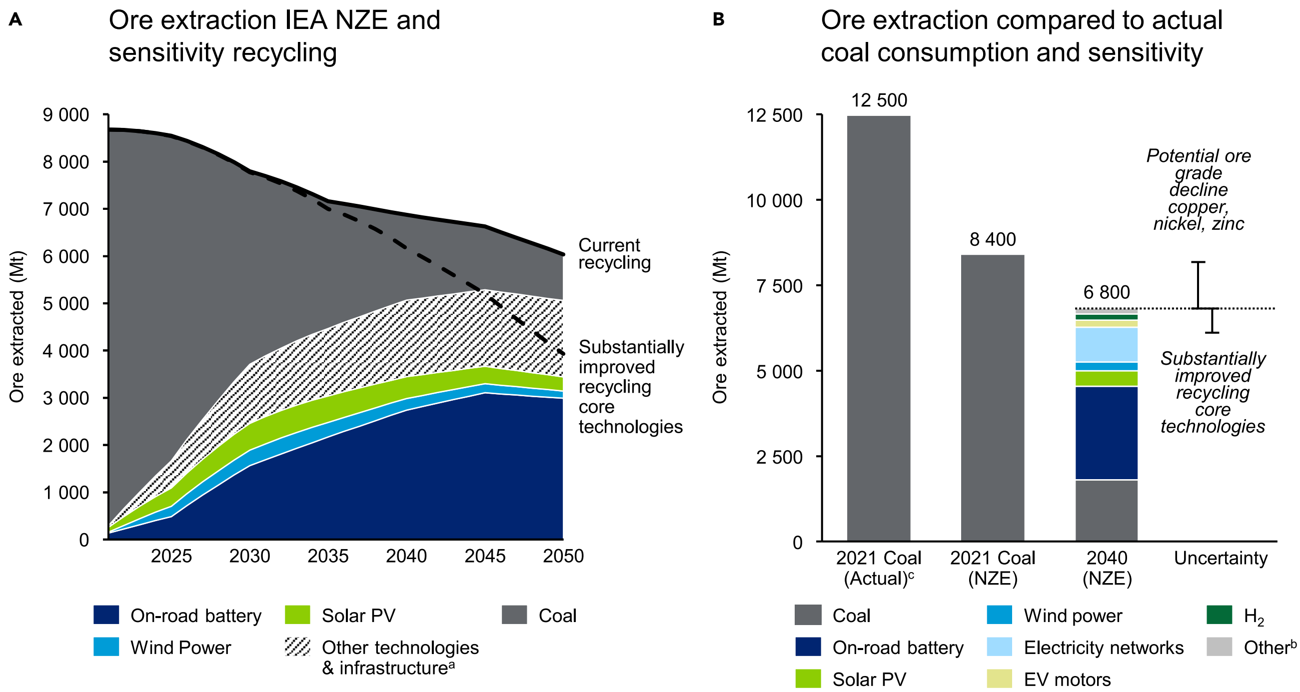

Figure 1. Comparison of ore extraction in IEA NZE scenario and sensitivity of substantially improved recycling and potential ore grade decline

(A) Annual IEA NZE ore and coal run-of-mine extraction for core technologies (solar PV, wind power, on-road battery) and other technologies and infrastructure defined by the IEA,[1] and coal based on extraction ratios for run-of-mine coal to production-ready coal. Estimates for the material requirements of other technologies and infrastructure are defined by the IEA[1] and are less certain than those for core technologies.

(B) 2021 actual and NZE run-of-mine coal extraction vs. estimated 2040 ore extraction for core technologies (solar PV, wind power, on-road battery) and other technologies and infrastructure mineral demand considered by the IEA NZE,[1] "including uncertainty for ore grade decline (copper, nickel and zinc) and substantially improved recycling for core technologies".

[a]Other technologies and infrastructure: electricity networks, EV motors, H_2.

[b]Other: hydro, bioenergy, CSP, geothermal, grid storage, and nuclear.

[c]Actual 2021 coal use was higher than in the NZE scenario as the world saw additional coal use and did not meet the NZE trajectory.

reduced with substantially improved recycling from 2035 onwards with a total reduction in 2050 of 2,100 Mt (core technologies recycling) (Figure 1A and supplemental information sections 2 and 3 for further details).

In terms of specific materials required, copper accounts for 80% of total PV ore extraction for current recycling rates (Figure 2A). Wind power requires a more diverse set of elements with copper, iron, and zinc driving approximately 90% of extractions and rare earth elements (REEs) together account for approximately 10%. Toward 2050, the share of iron and remaining "other" materials (consisting of various metals, silicon, and graphite) declines, and the share of zinc and REE ore extraction increases (Figure 2B). EV-related ore extraction is dominated by copper (60%–70%), followed by nickel (20%–30%) (Figure 2C). Overall, iron, aluminum, copper, graphite, silicon, and nickel represent the largest mineral extractions (Figure 2D). Of the total ore extraction related to the core technologies, 60%–70% is associated with copper demand and 10%–30% with nickel. The remaining 4 of the top 6 metals are lithium, iron, zinc, and aluminum.

Right-sizing mining activity expectations

We find that the energy transition will very likely result in an overall decreasing scale of mining activities globally. This suggests that the popular discourse claiming unprecedented increases in mining activities for the energy transition requires important nuance.[2] Namely, the unprecedented increase in mining activities for energy transition technologies stressed in previous research[1,4,10] is put into perspective by an even bigger decline in mining activities for fossil fuels, especially coal. The mass of minerals demanded for the energy transition technologies is a fraction of the mass of coal produced in the current fossil-dominated energy system (see supplemental information section 2.2 for further details), which would arguably further increase in a business-as-usual scenario due to increasing global energy demand.

There are several uncertainties that may increase or decrease our overall estimate. However, these would likely not impact our main finding. We demonstrate these uncertainties in

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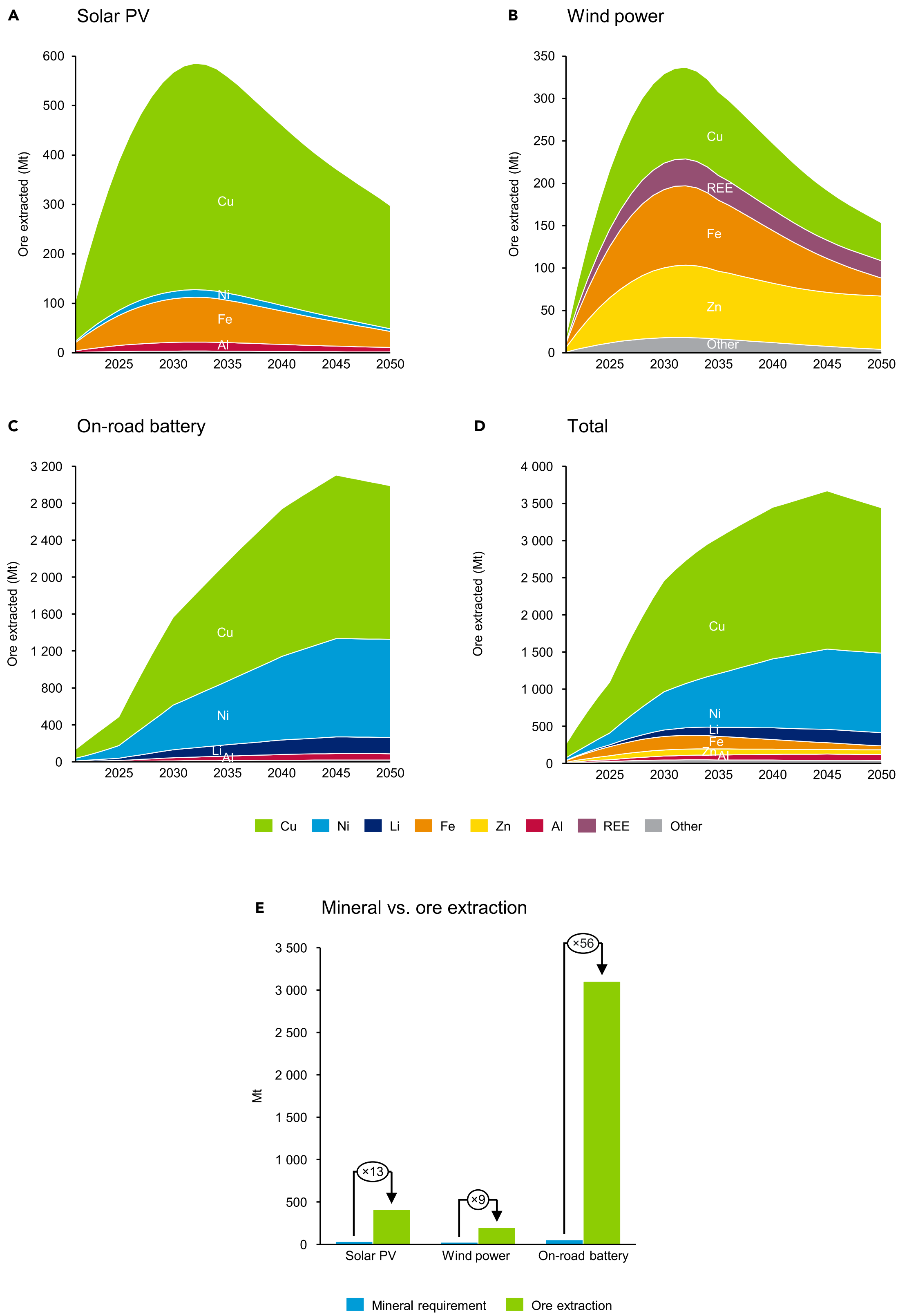

Figure 2. Technology-specific ore extraction per mineral annually and in the peak year in the current recycling scenario

(A–C) Ore extraction for the top 4 minerals for (A) solar PV, (B) wind power, and (C) on-road battery.

(D) Solar PV, wind power, and on-road battery total annual ore extraction for the top 6 minerals.

(E) The difference between minerals required and the ore extracted in the peak ore extraction year (2045) for the different technologies.

Figures 1A and 1B by varying recycling rates and potential ore grade declines. These could have an impact on absolute results but do not impact the conclusion as our estimates for overall ore extraction by 2040 would remain well below 2021 coal extraction levels. However, less ambitious energy transition pathways with lower reductions in coal production, such as in the IEA stated policies scenario (STEPS), would likely result in at least equal mining activities in 2040 compared to current mining activities in the NZE scenario (see supplemental information section 2.6 for further details).

Other uncertainties include other material extraction considerations other than ore grades and extraction ratios for run-of-mine coal, such as novel extraction approaches including deep-sea mining (see supplemental information section 2.4 for further discussion). Further, additional fossil-related material extraction from oil and gas could be considered, but these fossil fuels cannot be compared to metal ore extraction in the same way coal mining can. Oil and gas extraction, along with its infrastructure, is similarly associated with major land impacts, movement of material, and environmental burdens (see supplemental information sections 3.2, 3.3, and 3.4 for more). With the expected shift in mining, these impacts and burdens are subject to the changing geographical distribution of mining activities, as well as changes in the concentration of mining activities in the energy transition.

Mining activities for core technology expansions in the IEA NZE scenario will likely surpass the declining scale for fossil energy toward the middle of the century (see supplemental information sections 3.1 and 3.2 for further results and analysis). As such, despite the decreasing scale of overall mining activities, substantial energy transition-related mining activities remain. Previous work is based on a limited and location-specific case comparison of mining for wind vs. coal energy and found that substitution of 1 GW of coal-based electricity production with wind power would reduce required mining significantly. It also omits EV batteries, which we find to be the largest driver of mining activities in the NZE scenario.[2]

Given the level of ore demand, EV batteries warrant special focus for material reductions. Options for reduction include modal shifts toward electric bikes, public transport, and walking, among others.[9] This would reduce material demand related to all EV components (including EV motors), while reducing the need for such extensive electricity network infrastructure expansions. A second pathway is to reuse or repower end-of-life batteries, which could lengthen the lifetimes of EV batteries and thus reduce primary ore demand or reduce ore extraction requirements for other battery applications.[11] However, this would decrease the amount of material available for recycling. Finally, over a longer time frame, novel technologies could drastically lower battery-related mineral demand for nickel and copper in particular, but the mineral intensity of next-generation battery chemistries remains uncertain and could even increase demand for some battery minerals. For example, solid-state battery chemistries could increase lithium demand by up to 28%.[11]

The most important metals for overall ore extraction in the energy transition are copper and nickel due to the combination of their large-scale use and relatively low ore grades. Future copper demand is most influential as it requires the highest ore extraction for core technologies, along with an estimated 40% of the demand for electricity network additions.[1] The high demand for copper and nickel can be reduced via recycling, but technology-specific methods are required, particularly in EV battery capacity since these metals are embedded in the battery pack. Here, it is also likely that innovations will reduce material demands further as energy densities are found to continue to improve over time.[1] The majority of copper for solar PV and wind power can already be recycled through conventional recycling methods.[11,12]

The proven potential of recycling decommissioned energy transition technologies highlights the possibility of managing the stocks of minerals in society, whereas a fossil energy system has a continuous need for mining to extract dissipative fossil fuels. This difference indicates that a post-transition renewable energy system can be maintained with a fraction of the ongoing mining activities of a fossil energy system.

This is not to say the focus should be on the supply-side production of new energy technologies alone. As mentioned, demand-side measures will be essential, especially modal shifts to walking, cycling, and public transport, which can limit the overall amount of materials required in society for transportation services. Further, building retrofits can lower the materials required for renewable energy and ensuring high participation rates of EV owners in the electric grid storage market can lower materials requirements for stationary electricity storage.

Special policy attention is needed to prioritize the recovery and recycling of materials in this stock-based future energy system, especially for copper and nickel.

It is important to "right-size" expectations of the scale of mining so that popular arguments surrounding energy transition mining activities are not used as a reason for delay. Fears of an ever-increasing scale of mining activities in the energy system are unfounded. However, even though the overall scale of mining activities will likely decrease, efforts will be needed to limit the amount of material required for societies' energy services while ensuring the responsible sourcing of these materials.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2023.10.005.

AUTHOR CONTRIBUTIONS

J.N. and P.B. lead the writing and analysis. J.N. and R.K. designed the research. J.N. conducted the modeling. O.K. and R.K. supervised. All authors (O.K., R.K., B.S., J.N., and P.B.) contributed to the conceptualization, writing, and editing of the work.

DECLARATION OF INTERESTS

O.K. and J.N. are employed by Deloitte, a global provider of professional services, but worked on this project in a personal capacity. The information and views set out in this article are those of the authors and not necessarily reflect the official opinion of the company. P.B. Owns a number of different energy shares.

REFERENCES

1. IEA (2021). The Role of Critical Minerals in Clean Energy Transitions. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.
2. Krane, J., and Idel, R. (2021). More transitions, less risk: How renewable energy reduces risks from mining, trade and political dependence. Energy Res. Social Sci. *82*, 102311.
3. Sonter, L.J., Dade, M.C., Watson, J.E.M., and Valenta, R.K. (2020). Renewable energy production will exacerbate mining threats to biodiversity. Nat. Commun. *11*, 4174.
4. Hund, K., Porta, D. la, Fabregas, T.P., Laing, T., and Drexhage, J. (2020). Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf.
5. Nassar, N.T., Lederer, G.W., Brainard, J.L., Padilla, A.J., and Lessard, J.D. (2022). Rock-to-Metal Ratio: A Foundational Metric for Understanding Mine Wastes. Environ. Sci. Technol. *56*, 6710–6721.
6. Priester, M., Ericsson, M., Dolega, P., and Löf, O. (2019). Mineral grades: an important indicator for environmental impact of mineral exploitation. Miner. Econ. *32*, 49–73.
7. Lèbre, É., Stringer, M., Svobodova, K., Owen, J.R., Kemp, D., Côte, C., Arratia-Solar, A., and Valenta, R.K. (2020). The social and environmental complexities of extracting energy transition metals. Nat. Commun. *11*, 4823.
8. Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M.A., Kinnaird, J., Littleboy, A., et al. (2017). Mineral supply for sustainable development requires resource governance. Nature *543*, 367–372.
9. IEA (2021). Net Zero by 2050 - A Roadmap for the Global Energy Sector. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.
10. Kleijn, R., van der Voet, E., Kramer, G.J., van Oers, L., and van der Giesen, C. (2011). Metal requirements of low-carbon power generation. Energy *36*, 5640–5648.
11. Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., and Steubing, B. (2020). Future material demand for automotive lithium-based batteries. Commun. Mater. *1*, 99.
12. Elshkaki, A., and Graedel, T.E. (2013). Dynamic analysis of the global metals flows and stocks in electricity generation technologies. J. Clean. Prod. *59*, 260–273.