Mining for the Energy Transition: Creating a Just and Circular Economy

The mining and production of materials for lower-carbon and digital technologies remains a significant challenge to facilitating a just energy transition and circular economy. Recent research suggests practical and experimental pathways to accomplish material self-sufficiency.

We recommend attentiveness to local concerns, improving transparency, regulatory enforcement and re-organizing economic priorities.

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SUMMARY

Recent sustained growth in electric vehicles, solar panels, wind turbines and digital "smart" technologies all require an enormous amount of materials such as copper, cobalt, lithium, nickel, graphite, rare earth elements and hydrocarbons.[1, 2] Secure supply of these energy transition minerals is further prone to unexpected demand hikes and excludes the production of numerous infrastructures and devices, such as secondary energy transformers, electric scooters and other digital technologies.[3] While new mining technologies are expected to create greater efficiency, ore deposit qualities are declining (increasing the energy-use for production ratio), and researchers indicate that the material demand exceeds existing global reserves.[4]

The resulting environmental, social and economic impacts alongside the energy use required for extracting these minerals remain central concerns, not only for mining industries, but for market societies generally. Our research[5] indicates these concerns are valid and require more thoughtful action. The onset of ecological, social and climatic concerns only makes attentiveness to mining products more important.

We recommend the following immediate and long-term policy approaches to facilitate a just energy transition and circular economy.

RECOMMENDATIONS

Immediate

1. Improve transparency & data collection

- Make the energy and carbon footprints of mines public and better account for domestic and overseas consumption of extracted minerals.
- Increase public relations in local communities to explain mine operations and challenges.
- Provide greater detail about the material production and energy use of mine technologies.
- Extend and apply multi-method analysis to account for the social, environmental and economic (SEE) cost of lower-carbon equipment or power generating systems (e.g., digital operating systems, wind and solar facilities and biofuels; see Policy Brief 3: Solar Infrastructure).

2. Strengthen federal and state environmental regulations

- Water, air and soil quality standards should become stronger and enforced.
- Mines and related infrastructure should optimize their environmental mitigation efforts, for example, with more sophisticated water use plans, more detailed environmental impact assessments and improved land use and reclamation procedures.
- Smelters should be upgraded for worker safety and environmental protection with state and federal assistance.
- New mines or expansions related to existing mines should apply the principles of free, prior and informed consent (FPIC) to all regional inhabitants (and affirm the right to say “no”).
- All mines should consider bonding clauses and dedicate between 5-10% of annual revenue to funding future mine decommissioning and restoration.

Long-Term

1. Prioritize social and ecological sustainability

- The mining (and production) of new materials should be organized towards lower-carbon technologies.
- Hydrocarbon and mineral extraction companies could strategically downscale towards ecologically sustainable extractive methods.
- Local, state and federal governments should offer incentives to support industrial downscaling.
- Enact federal and state planning measures to facilitate extractive downscaling and society-wide circular economic planning.

The Kennecott Mine outside Salt Lake City, Utah.

1. Fressoz, Jean-Baptiste. *More and More and More: An All-Consuming History of Energy.* London: Allen Lane, 2024.
2. IEA. “Critical Minerals Data Explorer – Data Tools.” The International Energy Agency, 2024. https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer.
3. Dunlap, Alexander. “The Green Economy as Counterinsurgency, or the Ontological Foundations for Permanent Ecological Catastrophe.” *Environmental Policy and Science* 139, no. 1 (2023): 39–50. https://doi.org/10.1016/j.envsci.2022.10.008
4. Michaux, Simon P. “The Mining of Minerals and the Limits to Growth.” *Geological Survey of Finland: Espoo, Finland,* 2021, 1–72.
5. Dunlap, Alexander A., Bojana Novaković, and Benjamin K Sovacool. “Mining as Environmentalism: Green/Grey Extractivism and the Production of Extractive Subjectivities around the Rio Tinto Kennecott Mine in the United States.” *Globalizations*, 2025, 1–25. https://doi.org/10.1080/14747731.2025.2465069.

Manufacturing Sustainability: Towards More Equitable Solar Energy Factories

The production of solar panels remains essential to facilitating a just energy transition. The manufacturing of solar panels can be made more socially and ecologically sustainable.

We recommend improving labor, material sourcing and accountability practices.

SUMMARY

The last decade has witnessed the solar panel industry rapidly grow. Solar panel energy production efficiency has increased while production costs have decreased, leading to booming solar markets.[1] The production of solar panels entails fabricating panels with numerous hazardous materials. Different solar panels contain numerous toxic materials, such as arsenic, cadmium telluride and lead-selenium. Concerns related to mining and hazardous materials have made solar panel production an increasingly important issue.

Our research[2] examining a US solar panel factory reveals high standards of excellence, but also areas that could be improved.

First Solar building, Perrysburg, Ohio.

A solar array in Bowling Green, Ohio.

RECOMMENDATIONS

Improve transparency & data collection

- While efforts towards transparency exist, they frequently omit detailed information regarding material use. We call for more granular data on silicon, steel, glass and shipping materials, including their quantity and associated embodied carbon emissions.
- Increasing public relations efforts and outreach to local residents about the operations of the solar industry would benefit local communities (e.g., public announcements, news, schools and events/tours at the facility).
- Accounting for the material and energy-intensive supply web of digital automation and assembly line equipment would allow more accurate environmental sustainability assessments.

Change labor relations

- Shift hours were not ideal for workers and made scheduling for upskilling courses at higher-education institutions difficult, limiting opportunities for career advancement.
- H1B1 visas were seen to obstruct career pathways of locals to lower and middle-management positions.
- Leniency for leaving facilities during work hours for medication or other emergencies is advisable. (Arbitrary or unfair termination practices of low-level workers were reoccurring).

Address the social and environmental impacts of warehouse expansion

- New constructions should require obligatory dust mitigation measures.
- Mitigate wildlife displacement and employ legitimate offsetting strategies.
- Support neighbors impacted by solar factories with free or discounted solar panels.
- Offer greater communication with neighbors and residents and institutions concerning manufacturing operations, expansions and employment opportunities.

Calibrate business models

- Diversify solar products to include rooftop, vertically integrated building panels and other solar systems.
- Consider shared ownership approaches to community solar, which would enable groups to take advantage of utility-scale deployment using thin-film commercial panels.
- Greater priority should be placed on manufacturing solar panels for buildings and structures (as opposed to deserts, farmland and forests).

1. The Economist'. *Dawn of the Solar Age.* New York: Profile Books, 2024.
2. Dunlap, A and BK Sovacool. ""It's Kind of Just Another Factory:" A Political Ecology of Solar Panel Manufacturing in Perrysburg, Ohio," *Journal of Political Ecology* 32(1) (January, 2025), pp. 1-32.

Solar Siting, Deployment and Operation: Improving the Governance of Solar Infrastructure

Solar photovoltaic panels are an essential technology for the energy transition. Although an important energy and climate mitigation tool, they can still have large-scale and negative impacts on ecosystems. These impacts are related to the placement, size, mitigation and restoration measures established (or not) on land. Concentrated solar power (CSP) facilities have negative impacts on land use, water and Indigenous burial grounds.

We recommend stronger governance protections concerning the deployment of solar facilities on desert, forested or agricultural lands and, instead, prioritizing their placement on buildings and structures already occupying land.

SUMMARY

According to the Solar Energy Industries Association (SEIA), the US has over 235 gigawatts (GW) of solar capacity installed nationwide, which estimates say is enough to power over 40 million homes.[1] The western US, specifically the deserts of California, Nevada, Arizona, Utah and New Mexico, have seen a dramatic increase in solar development. Our research [2, 3, 4, 5] examining a solar deployment in eastern California reveals numerous concerns. Although not as damaging as fossil fuel infrastructures, solar panels depend on hydrocarbons for mining and manufacturing (see Policy Briefs 1 and 2 on Mining and Solar Manufacturing) and large-scale solar facilities require razing the land, irreparably harming endangered species, animal and insect populations. Solar panels and, in particular, CSP facilities also require enormous amounts of water, not only to stabilize the construction of solar facilities but also to wash the panels to maximize their solar absorption. Mitigation measures, moreover, did not fare well against intense rain and sandstorms in desert environments. Deserts are also invaluable carbon sinks, which solar development significantly disrupts.

We divide our recommendations between utility-scale solar facilities and rooftop solar.

UTILITY-SCALE SOLAR PROJECTS

Improve transparency & data collection

- There remains a lack of and incomplete guidance concerning environmental impact assessments (EIAs), which often fail to account for topographical changes related to rapid solar development.
- There needs to be greater procedural and governance transparency from local developers, state regulators and the federal government. Both California residents and members of the Colorado River Indian Tribes expressed concerns that they were excluded and felt “sacrificed” by the rapid enclosure and development of solar panels or CSP solar facilities.
- Ensuring the transparency and distribution of funds from solar projects to the rural residents or tribal groups impacted by them remains essential.
- Implementing more advanced corruption threat assessments and anti-corruption risk mapping and enforcement remains essential.

Change labor relations

- Hire local laborers and promote upskilling. Solar developers initially relied on unions and out-of-state workers from locations two to three hours away from the region.
- The temporary employment generated by construction of solar facilities presented long-term employment challenges.

Recognize and address environmental impacts

- De-prioritize solar development on deserts, forests and agricultural lands.
- Prioritize solar panels on homes, parking lots, buildings and other urban structures.
- Agrovoltaics and solar panels over canals are worth considering, but need to consider the potential for solar panels to crack and leak from extreme weather events and birds crashing into them (as birds are recorded confusing a large assortment of solar panels for lakes).

RETHINK ROOFTOP SOLAR DEPLOYMENT

- Promote greater education among the general public and/or homeowners regarding rooftop solar development.
- Task consumer protection agencies with holding rooftop solar sales and installer companies accountable.
- Strengthen regulations regarding consumer protection and enforcement against unethical and misleading solar panel selling, installation and maintenance practices.
- Offer tax breaks and subsidies for all citizens, but especially low-income neighborhoods, to support the installation of solar panels.

Solar panels in Blythe, California.

1. SEIA. “Solar Industry Research Data.” Solar Energy Industries Association, 2024. https://seia.org/research-resources/solar-industry-research-data/.
2. Dunlap, Alexander A., Benjamin K Sovacool, and Bojana Novaković. “‘Our Town Is Dying:’ Exploring Utility-Scale and Rooftop Solar Energy Injustices in Southeastern California.” *Geoforum* 156, no. 1 (2024): 1–15. https://doi.org/10.1016/j.geoforum.2024.104120.
3. Sovacool, BK, A Dunlap, and B Novakovic. “When Decarbonization Reinforces Colonization: Complex Energy Injustice and Solar Energy Development in the California Desert,” *Annals of the American Association of Geographers* 115(3) (March, 2025), pp. 640-670.
4. Dunlap, Alexander, Benjamin K. Sovacool, and Bojana Novaković. “‘A Dead Sea of Solar Panels:’ Solar Enclosure, Extractivism and the Progressive Degradation of the California Desert.” *The Journal of Peasant Studies* 52, no. 3 (2025): 539–73. https://doi.org/10.1080/03066150.2024.2388051.
5. Sovacool, Benjamin K., Bojana Novaković, and Alexander A. Dunlap. “Sex for Solar? Examining Patterns of Public and Private Sector Corruption within the Booming California Solar Energy Market.” *Energy Strategy Reviews* 59 (2025): 1-9. https://doi.org/10.1016/j.esr.2025.101727.

Solar Panel Disposal: Towards Accountability and Recycling

The environmental impact of solar panels is intimately linked to whether and how they are decommissioned. We have found that solar panels are frequently landfilled, and also claims of recycling solar panels often entail only recycling a small percentage of the panel.

We recommend new regulations and incentives to support solar panel recycling.

A solar panel recycling facility in Yuma, Arizona.

SUMMARY

Solar panel lifespans are between 25-35 years.[1] This lifespan can be reduced within environments experiencing extreme cold and heat. There remains an enormous wave of millions, if not billions, of solar panels ready for decommissioning.

Our research into solar panel disposal and recycling indicates a looming crisis, one that guides our following recommendations.

A building near the First Solar Facility in Perrysburg, Ohio.

RECOMMENDATIONS

Improve transparency & data collection

- End-of-life tracking and accountability must be documented, enforced and made public. This could entail solar panel recycling certification programs managed and enforced by the state as opposed to third-party and voluntary enforcement.
- This further entails stringent regulation regarding hazardous waste.

Change labor relations

- City planners should consider classifying recycling facilities as medium-to-heavy industrial zones.
- Fair labor conditions and safety precautions must be monitored and enforced.

Reform government incentives

- Solar panel recycling and facility support should be incentivized through tax breaks and subsidies.
- Similar to other electronic devices, such as televisions, a recycling tax should be built into the price of the panels.
- Impose regulations against companies speculating on solar panel decommissioning.
- Disincentivize solar panel land filling through fines and regulations.
- Encourage recycling by assisting in subsidizing and streamlining facility construction and safety.
- Advance strategies to facilitate communication between solar panel operators and recyclers.
- Design products for disassembly (and recycling).
- Encourage the right to repair and solar panel retrofitting, and life extension.
- Promote loan programs with low interest rates and long payback times.

Subsidies and tax breaks could be limited for 3-5 years or conditioned on the priorities above.

1. Mulvaney, Dustin. Solar Power: *Innovation, Sustainability, and Environmental Justice.* Berkeley: University of California Press, 2019.