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Mandate of the Special Rapporteur on the promotion and protection of human rights in the context of climate change

Annex II - Further considerations

To the report of the Special Rapporteur on the promotion and protection of human rights in the context of climate change, Elisa Morgera, titled 'A human rights-based approach to the energy transition (A/80/188)

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Annex II - Further considerations

This annex provides further sources (UN reports, academic and grey literature, as well as submissions made in preparation for the report, which are available at https://www.ohchr.org/en/calls-for-input/2025/call-inputs-human-rights-life-cycle-renewable-energy-and-critical-minerals), in order to complement those cited in the report itself.

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1. Overall progress in the energy transition

According to the 2025 UN System's report on renewables and energy efficiency,[1] solar and wind power "are now almost always the least expensive — and the fastest — option for new electricity generation." Specifically, the report highlighted that:

- between 2010 and 2022, solar and wind power "became cost-competitive with fossil fuels without financial support in many countries"; and
- in 2024, "the global average electricity generation cost from solar PV was 41% cheaper, and onshore wind 53% cheaper, than the least-cost new fossil fuel-fired power plant".

The UN System's report also indicated that "growth in renewable energy is now outpacing that in fossil fuels in the power sector", with 92.5% of all new electricity capacity additions and 74% of electricity generation growth derived from renewables in 2024. The UN System's report further underscored that "renewable energy can boost energy access, affordability, and security." In comparison, those living in countries that are net importers of fossil fuels (74% ca of the global population) are exposed to higher costs of living (including heating, cooling, lighting, and mobility, and indirectly the costs of other goods and services throughout global supply chains) due to the volatile prices, supply disruptions, and geopolitical turmoil linked to fossil fuels.

The UN System's report further clarified that "centralized and decentralized renewables-based systems also offer the most cost-effective and fastest solutions for delivering universal clean energy access by 2030", with a combination of grid, mini-grid, and off-grid renewable solutions, especially in difficult-to-reach rural locations where eight out of ten people without access to electricity live. The report also referred to studies demonstrating that the implementation of small-scale renewable energy microgrids in developing countries has significantly contributed to improved livelihoods, food security, health, and education, as well as reduced poverty and pollution exposure.

The UN System's report, on the other hand, underscored that the share of fossil fuels in global total energy supply only decreased from 83% to 80% between 2015 and 2024 due to continued fossil fuel expansion, combined with limited progress in improving energy efficiency and advancing the electrification of all end-use sectors. The report further noted barriers to the energy transition emerging from international investment agreements.[2] Academic studies confirm that there is a growing number of costly investor–state disputes and threatened disputes under international investment agreements that are challenging renewable energy development.[3] In this connection, the recommendations on a fundamental reform of

[1] United Nations. Seizing the moment of opportunity: Supercharging the new energy era of renewables, efficiency, and electrification (2025).
[2] Ibid.
[3] Ladan Mehranvar and Sunayana Sasmal. The Role of Investment Treaties and Investor-State Dispute Settlement in Renewable Energy Investments (Columbia Center on Sustainable Investment, 2022).

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international investment law in the 2025 report to the Human Rights Council on the Imperative of Defossilizing our Economies (A/HRC/59/42, paras 83-84) are reconfirmed.

2. Energy inequalities

According to a 2025 Oxfam report, if one year's energy consumption of the wealthiest 1% were redistributed, it could meet the modern energy needs of all the people in the world without electricity seven times over, while redistributing the consumption of the top 10% global energy consumers could meet the needs of the entire Global South nine times over. [4]

The same report underscored that Global South could be at the heart of a global just transition: in almost complete reverse to patterns of energy investment, 70% of the world's untapped renewable potential lies in the Global South. The potential to radically transform the energy landscape is tangible. Harnessing less than 1% of the annual solar energy from the Sahara Desert could power all of the Middle East and North Africa for a whole year. Tapping into less than 1% of usable wind energy globally could provide electricity to South-East Asia's 677 million residents. The estimated cost of this wind power, US$321bn, could have been raised globally in the first 10 months of 2024 through a fossil-fuel corporation profits tax.[5]

3. Solar energy

The technical potential of direct solar energy lies beyond the potential of any other renewable energy resource, far above the global consumption of energy. With low operational costs, solar photovoltaics (PV) has become increasingly competitive with other energy sources. Costs have declined drastically in the last ten years, and are expected to fall further over the next years. The costs of concentrating solar power (CSP) have also fallen, although less significantly. This makes it harder to compete with photovoltaic, although CSP has the advantage of storing heat for a longer period of time. The cost of PV grid integration can still be high in certain places, but this can be reduced through grid flexibility. [6]

Off-grid solar panels have improved energy access, especially in remote areas.[7] Distributed solar or mini-grid projects can expand access to clean energy for rural and marginalized communities, supporting rights to education, health services, and economic opportunities.[8] For these reasons, solar energy has long been considered a suitable energy source to achieve local energy sovereignty.[9] The construction of renewable energy facilities can stimulate the local

[4] Oxfam, Unjust Transitions: Reclaiming the energy future from climate colonialism (2025).
[5] Ibid.
[6] IPCC, Sixth Assessment Report (2022), 630-632.
[7] Submission by Namati.
[8] Submission by Global Health and Climate Alliance (GHCA).
[9] Schelly et al., "Energy policy for energy sovereignty: Can policy tools enhance energy sovereignty?", *Solar Energy*, Vol. 205 (2020a) 109-110; see also Sovacool et al., "Beyond cost and carbon: The multidimensional co-benefits of low carbon transitions in Europe", *Ecological Economics*, Vol. 169 (2020) 8.

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economy of rural communities that struggle with socio-economic challenges, such as unemployment and ageing populations.[10] Given that small-scale solar projects are highly cost effective, and that they can provide power for lights, irrigation systems, refrigerators and communication tools, it is an energy source that can provide direct benefits to local communities. Even though initial costs are relatively high, there is no heavy maintenance. The solar energy can also be an active source of income if power can be transferred to the grid and sold to utilities.[11]

Government policies can support small-scale options that require less capital and support the solar installation and maintenance for households that are unable to finance them.[12] Due to regulatory limitations and a lack of incentives, however, public participation and investment in solar energy is sometimes undermined currently, which makes it less economically viable.[13]

Generally, the solar industry creates a lot of jobs.[14] Given that it is labor intensive compared to other traditional methods for electricity generation, further deployment of solar energy can lead to significant new job creation.[15] Nevertheless, labour rights are also compromised in many projects, with reported cases of low wages, poor conditions, and union suppression in solar panel manufacturing.[16]

Solar energy also has an impact on the environment. To minimize negative impacts of PV, materials should be recycled and smart land-use choices should be made.[17] The development of large-scale solar parks inevitably entails changes for the local ecosystem.[18] In mountainous areas, solar parks can impact the microclimate by increasing the atmospheric temperature and decreasing the relative humidity, an effect that gradually intensifies over time. A similar heating effect takes place in desert and semi-arid climates, where the effect has been labeled as the 'PV heat island'.[19] In other instances, however, solar parks can function as cold-sources by lowering temperatures in and around the park.[20]

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[10] Okkonen et al., "Socio-economic impacts of community wind power projects in Northern Scotland", *Renewable Energy*, Vol. 85 (2016) 826.
[11] Dreveskracht, "Economic Development, Native Nations, and Solar Projects", *American Journal of Economics and Sociology*, Vol. 72, No. 1 (2013) 127.
[12] Sovacool et al., "Towards improved solar energy justice: exploring the complex inequities of Towards improved solar energy justice: exploring the complex inequities of household adoption of photovoltaic panels", *Energy Policy*, Vol. 16 (2022) 11.
[13] Submission by Greenpeace Southeast Asia.
[14] Sovacool et al. (n 9), 7.
[15] Croucher, "Capacity factors and solar job creation", *Energy Policy*, Vol. 39 (2011), 6914-6915.
[16] Submission by University of Venda, South Africa.
[17] IPCC (n 6), 632.
[18] Zhang et al., "Climate environmental impact analysis of a mountain photovoltaic plant", *Solar Energy*, Vol. 282 (2024), 1; see also Guerin, "A case study identifying and mitigating the environmental and community impacts from construction of a utility-scale solar photovoltaic power plant in eastern Australia", *Solar Energy*, Vol. 146 (2017) 99.
[19] Zhang et al (n 18), 9.
[20] Hua et al., "The Influences of the Desert Photovoltaic Power Station on Local Climate and Environment: A Case Study in Dunhuang Photovoltaic Industrial Park, Dunhuang City, China in 2019", *Atmosphere*, Vol. 23 (2022) 10.

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The development of solar parks can lead to the release of carbon dioxide from terrestrial ecosystems. This is especially the case in areas with previously undisturbed land.[21] Solar park development on land, thus inevitably entails changes for the ecosystem.[22]Sometimes, these lands are very biodiverse and characterized by distinctive ecological features. [23] Animal hiding spots, preying strategies and food availability can all be affected.[24] In the case of concentrating solar power technology, large quantities of insects may be burned in the process.[25] The power plants can create linear barriers that are unsurmountable for certain species, complicating the gene flow between populations. Habitat loss and fragmentation risk negatively impacting biodiversity.[26] A crucial first step is to choose areas where the impact on biodiversity would be low, considering the spatial distribution of species. [27] Then, some of the worst effects can be mitigated by creating openings in fences, or providing corridors.[28] Overall, however, solar power is considered more efficient compared to other energy sources, with the potential to limit land competition.[29]

By developing solar energy on rooftops, on brownfields or by using agrivoltaics, pressure on land can be reduced.[30] Agrivoltaics allow solar energy production and agricultural activities to be combined on the same plot. This helps to preserve arable land, to strengthen crop resilience in the face of climate change (by reducing evapotranspiration and protecting against heat waves), and to ensure a more equitable distribution of benefits between energy operators and rural communities. [31]

4. Wind energy

Like solar energy, wind energy has become more competitive with other sources of electricity. In the last ten years, costs have declined significantly for onshore and offshore wind energy, and those costs are expected to fall further through technological advancements and scale-ups. The estimated technical potential and available wind energy exceed the amount of energy needed to limit global warming far below 2°C. Even though wind resources are distributed unevenly across the globe, there are hotspots on every continent – mostly in coastal areas.

[21] Hernandez et al., "Environmental impacts of utility-scale solar energy", *Renewable and Sustainable Energy Reviews*, Vol. 29 (2014) 771.
[22] IPBES-IPCC Co-sponsored Workshop: Biodiversity and Climate Change – Scientific Outcome (2021), 55; Zhang et al (n 18); Guerin (n 18).
[23] Ohdedar, "Climate adaptation, vulnerability and rights-based litigation: broadening the scope of climate litigation using political ecology", *Journal of Human Rights and the Environment*, Vol. 13, No. 1 (2022), 150-151.
[24] Fthenakis et al., "Large photovoltaic power plants: Wildlife impacts and benefits", *37th IEEE Photovoltaic Specialists Conference* (2011) 12.
[25] Ibid.
[26] Guerin (n 18), 100; Hernandez et al., "Environmental impacts of utility-scale solar energy", *Renewable and Sustainable Energy Reviews*, Vol. 29 (2014) 769.
[27] Ibid.
[28] Fthenakis et al. (n 24), 12-13.
[29] IPCC-IPBES (n 22), 55.
[30] Submission by Landesa and the International Land Coalition.
[31] Submission by Bouramdane.

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Offshore infrastructure has the most post potential thanks to reliable, strong winds, but is also more expensive in terms of construction, maintenance and transmission.[32]

Wind farms create most jobs during the construction phase. People are hired through short-term contracts, and laid off once the infrastructure is ready for operation. While the income from these jobs can help people in local communities to invest in their livelihoods (e.g. by acquiring more cattle) or improve their living conditions, construction jobs are not a source for long-term income.[33] After the construction, some stable maintenance and operation jobs are created in the area. It happens frequently, however, that only few local people are recruited, and that they are remunerated badly.[34] Long-term jobs are mostly given to engineers and experts coming from cities further away or even from overseas.[35]

When communities are relocated to company-provided land, they are often left with inadequate water and are forced to buy food, as they can no longer rely on their own land.[36] The land use can also infringe on pasture lands, and complicate Indigenous methods of animal herding, such as the herding of reindeers.[37] In some instances, leasing can be part of the solution. Leasing allows landowners to retain ownership, receive rental income and recover land when the lease ends, with safeguards to prevent exploitative terms and ensure responsible decommissioning.[38]

Through the establishment of social enterprises, the social good of local communities can be promoted. Close cooperation with community members can reduce the dependency on imported energy while addressing local energy poverty.[39] Alternatively, developers can allocate a percentage of their profit to a fund that is managed by the local community to ensure that benefits flow back locally. It is important that promises made on that front are effectively realized. Local property taxes can also contribute to benefit-sharing.[40] There have been efforts by local governments to make wind farms contribute more fiscally, but it is a contentious issue, and companies often benefit from fiscally advantageous schemes.[41]

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[32] IPCC (n 6), 634-635.
[33] Frankline, "Land acquisition, renewable energy development, and livelihood transformation in rural Kenya: The case of the Kipeto wind energy project", *Energy Research & Social Science*, Vol. 112 (2024) 6.
[34] Huesca-Pérez et al., "Social implications of siting wind energy in a disadvantaged region – The case of the Isthmus of Tehuantepec, Mexico", *Renewable and Sustainable Energy Reviews*, Vol. 58 (2016) 954, 958.
[35] Brower Brown, "Wind power in northeastern Brazil: Local burdens, regional benefits and growing opposition", *Climate and Development*, Vol. 3, No. 4 (2011) 353; Dunlap, "'The Town is Surrounded:' From Climate Concerns to life under Wind Turbines in La Ventosa, Mexico", *Human Geography*, Vol. 10, No. 2 (2017) 28.
[36] Submission by Ligia Campos.
[37] Fjellheim, "Wind Energy on Trial in Saepmie: Epistemic Controversies and Strategic Ignorance in Norway's Green Energy Transition", *Arctic Review on Law and Politics*, Vol. 14 (2023); see also Nysten-Haarala et al., "Wind energy projects and reindeer herders' rights in Finnish Lapland: A legal framework", *Elementa Science of the Anthropocene*, Vol. 9, No. 1 (2021).
[38] Submission by Landesa and the International Land Coalition.
[39] Okkonen and Lehtonen (n 10).
[40] Frankline (n 33), 7.
[41] Serna, "Harvesting the Wind: The Political Ecology of Wind Energy in the Isthmus of Tehuantepec, Oaxaca", *PhD dissertation at the University of Manchester* (2020) 195-197.

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More generally, tools to ensure benefit-sharing include: local ownership or co-ownership through which shares in the energy development project are granted to the community, community funds provided by the developer, community benefits in kind provided by the developer, compensation packages, local employment opportunities, local energy-price reduction packages and indirect social benefits, including eco-tourism.[42]

Wind energy is considered an energy source with a small environmental footprint and little reliance on natural resources.[43] Nevertheless, there are environmental impacts. When wind farms are placed in ecologically sensitive areas, there have been recurrences of landslides and floods, bringing debris that damages crops and generally reducing the abundance, activity, behaviour and physiology of wild species.[44] When developing parks, it is crucial to choose areas where the impact on biodiversity would be low,[45] considering the spatial distribution of species. [46] Additionally, some of the worst effects can be mitigated by creating openings in fences, or providing ecological corridors.[47]

The development of wind farms can lead to a water crisis, and cause negative health impacts due to the noise generated by the towers' propellers.[48] Changes caused in coastal sediment flow and the filling of lagoons can lead to a decline in fishing. There also have been instances of deforestation, losses in food sovereignty and income sources, physical and mental health issues that include depression, sleep disorders, migraines and emotional distress. Local communities nearby wind mega-farms have seen an increase in crime, harassment and traffic accidents. There currently is a lack of adequate studies on the cumulative impacts of energy generation parks in traditional territories. The existing studies lack effective participation of local populations.[49]

5. *Marine energy*

Environmental impacts common to all marine renewables are the generation of underwater noise and electromagnetic fields, loss of biodiversity and the disruption of habitats and marine animals' lives, impacting biodiversity and peoples' livelihoods.[50] The food chain may also be

[42] Chapman et al., Wind Turbine Syndrome, *Sydney University Press* (2025), 273-274.
[43] Bruyninckx et al., "Global Resources Outlook. 2024: Bend the trend", *International Resources Panel* (2024), 138.
[44] Submission by Legal Initiative for Forest and Environment; Thaker et al., "Wind farms have cascading impacts on ecosystems across trophic levels", *Nature Ecology & Evolution* , Vol. 2 (2018).
[45] Fthenakis et al (n 24) 12.
[46] Guerin (n 16), 100; Hernandez et al. (n 26), 769.
[47] Fthenakis et al. (n 24), 12-13.
[48] Submission by Alianza por los Humedales Andinos.
[49] Submission by FGV Center for Human Rights and Business; Conectas Human Rights, Wind Farms, Socio-environmental Rights and Financial Institutions: The Case of Chapada do Araripe (2023).
[50] IPCC-IPBES (n 22), 56; Salvador et al., "Socio-economic, legal, and political context of offshore renewable energies", *WIREs Energy and Environment*, Vol. 12 (2023) 4.

affected.[51] Electromagnetic force generated by underwater cables affects the daily behaviour of sensitive animals, such as cetaceans and steelhead trout, and other organisms.[52]

5.1 Offshore wind and solar power

There are a range of marine clean energy technologies at varying stages of development, including bottom-fixed wind turbines, floating offshore wind systems,[53] as well as grid connections and energy storage.[54] Large-scale wind platforms are already operative in Europe and Eastern Asia, and their energy potential is forecasted to expand by 2030.[55] Offshore solar platforms are forecasted as the most promising marine renewables for the coming decade.[56]

The development of floating photovoltaics on bodies of water (such as irrigation basins and hydraulic reservoirs) or at sea ('offshore photovoltaics') can have several advantages, including natural cooling of the panels which improves their efficiency and the optimization of space use without encroaching on agricultural, industrial or construction land. Floating photovoltaics reduce water evaporation thanks to shading and conserves the quality of the water it covers by limiting the proliferation of algae. [57]

Nevertheless, there are risks for negative atmospheric effects of photovoltaics on the ambient flow-changes in the micro-climate, due to the large surface occupied and the temperature differences between the hot surface of photovoltaics and surrounding cold air.[58] Other environmental and ecological risks include a reduced penetration of sunlight which could affect the growth of algae and animals and the release of toxic elements. Those elements include lead and cadmium, hydrocarbon pollutants and microplastic particles that damage the marine ecosystem and organisms, but may also harm humans through the food chain.[59]

Due to difficult construction and operating conditions, the front-end investment cost of offshore wind power is typically higher than in onshore wind power.[60] Compared to on-shore wind

[51] Ouro et al., "Environmental Impacts from Large-Scale Offshore Renewable-Energy Deployment", *Environmental Research Letters*, Vol. 19 (2024), 4, at 8.
[52] Cui et al., "Marine Renewable Energy Project: The Environmental Implication and Sustainable Technology", *Ocean & Coastal Management,* Vol. 232 (2023), 2.
[53] European Commission, An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future, COM(2020)741, 3.
[54] Gao et al., "Techno-economic assessment of offshore wind and hybrid wind–wave farms with energy storage systems", *Renewable and Sustainable Energy Reviews*, Vol. 192 (2024) 114263.
[55] Cui et al. (n 52), 3; Farr et al., "Potential Environmental Effects of Deepwater Floating Offshore Wind Energy Facilities", *Ocean & Coastal Management*, Vol. 207 (2021), 1.
[56] Sheng et al., "Discussion on the Development of Offshore Floating Photovoltaic Plants, Emphasizing Marine Environmental Protection", *Frontiers in Marine Science,* Vol. 11 (2024) 11*,* 1.
[57] Submission by Bouramdane.
[58] Wu et al. "Discussion on the Development of Offshore Floating Photovoltaic Plants, Emphasizing Marine Environmental Protection" *Frontiers in Marine Science*, Vol 11 (2024) 5; Ouro et al., 2.
[59] Ouro et al. (n 51), 7-8.
[60] Sovacool et al., "Cost performance and risk in the construction of offshore and onshore wind farms", *Wind Energy*, Vol. 20 (2017), 891–908.

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power, however, offshore operations are typically more efficient due to larger turbine sizes and economies of scale[61] as well as reduced systemic costs due to more stable power output.[62]

Wind turbines are known for generating wakes – low speed turbulence on water surfaces- potentially extending 60 km or more, depending on their size and numerosity.[63] Research on turbines close to coastal cities showed increased evaporation and heat fluxes from the water surface and impacts on the microclimate, such as alteration in clouds that reduce precipitation levels and affect oceans' salinity. This can affect marine ecosystems and nearby offshore photovoltaics.[64] Wind turbines can also alter long-term meteorological patterns, such as the track and development of cyclones, but it is hard to predict the impact that offshore wind's deployment will have in the long turn. More specific, long-term studies are needed to understand how these platforms affect the oceans' surface.[65]

Other problems include changes in the migration pathways of birds.[66] The risk of bird collision is species-specific and depends on the size, visibility, and lighting used in wind platforms. It decreases with increased distance from the coast.[67] Offshore wind power may reduce, fragment and degrade habitat for wildlife, fish, and plants, particularly in the construction phase of the operations.[68] The mooring system poses a threat of entanglement, especially for whales.[69] Moreover, during their operation, spinning blades of the turbines pose a threat to avian species, such as birds and bats.[70] Noise from the blades may disturb animals, including marine mammals and fish.[71] Further, high-voltage transmission lines may be harmful to migratory fish and other marine species.[72] Electromagnetic force generated by underwater cables affects the daily behaviour of sensitive animals, such as cetaceans and steelhead trout.[73] During the

[61] Levitt et al., "Pricing offshore wind power", *Energy Policy*, Vol. 39 (2011), 6408.
[62] IEA, Offshore Wind Outlook 2019 (2019).
[63] Ibid. 2
[64] Ibid., 3
[65] Ibid.
[66] Cui et al. (n 52), 1.
[67] Farr et al. (n 55), 9.
[68] Snyder et al., "Ecological and economic cost-benefit analysis of offshore wind energy", *Renewable Energy*, Vol 34, No. 6 (2009); Klain et al., "Bird Killer, Industrial Intruder or Clean Energy? Perceiving Risks to Ecosystem Services Due to an Offshore Wind Farm", *Ecological Economics*, Vol. 143 (2018).
[69] Farr et al. (n 55), 9.
[70] It is worth noting, however, that wind energy causes only a small portion of all human-related killings of birds (1 out of 250). See Saidur et al., "Environmental impact of wind energy", *Renewable and Sustainable Energy Reviews,* Vol. 15 (2011), 2426; Erickson et al., "A comprehensive analysis of small-passerine fatalities from collision with turbines", *PLoS ONE*, Vol. 9 (2011) 9; IPCC-IPBES, Co-sponsored workshop report on biodiversity and climate change (2021), 55.
[71] Teff-Seker et al., "Noise pollution from wind turbines and its effects on wildlife: A cross-national analysis of current policies and planning regulations" *Renewable and Sustainable Energy Reviews*, Vol. 168 (2022).
[72] Taormina et al. "A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions", *Renewable and Sustainable Energy Reviews, Vol. 96 (2018)*.
[73] Cui et al. (n 52), 2.

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materials extraction and production stage, wind turbines produce emissions as they rely on the use of cement, which generates large quantities of CO_2.[74]

Offshore wind and solar power may conflict with other economic uses of the sea, such as shipping, fishing, and aquaculture.[75] Located further away from residential areas, floating photovoltaics cause less conflicts as the landscape alteration and noise is perceived less.[76] There is also competition for space with ecological needs of marine species, as it is not uncommon that potential sites for offshore power are in areas with high biodiversity values.[77] Photovoltaics can impact benthic communities and mobile species.[78] Marine renewables rely on the widespread use of bottom-fixed installations, which are limited to shallow waters due to technical and cost constraints, and require extensive sea-floor construction.[79]

The extent and nature of impacts on marine, biodiversity, transportation, and local climate remain unclear due to the lack of long-term data from geology, hydrology, and ecology.[80] The lack of scientific knowledge on the possible impacts of offshore wind power on marine biodiversity is a constant challenge.[81] Nevertheless, it is clear that offshore renewables risk causing irreversible damage to ocean environments, raising concerns about the long-term sustainability of these efforts.[82] Given the dependency of humanity on oceans for 'food, health, livelihoods, security, cultural continuity, and a good standard of life', negative environmental impacts also affect the human right to a clean, healthy and sustainable environment. [83]

Current regulation of offshore solar and wind does not sufficiently require consideration of ecological impacts and offers little legal protection for biodiversity and the marine environment, for example through the assumption that marine reenables more-or-less automatically fulfil the 'overriding public interest' requirement. In *Schwarze Sulm* (346/14), for example, the Court of

[74] Kramarz, "Governing the dark side of renewable energy: A typology of global displacements", *Energy Research and Social Scienc*e, Vol. 74 (2021) 5.
[75] See, e.g., Virtanen et al., "Balancing profitability of energy production, societal impacts and biodiversity in offshore wind farm design" *Renewable and Sustainable Energy Reviews*, Vol. 158 (2022), 2.
[76] Ladenburg, "Attitudes towards on-land and offshore wind power development in Denmark; choice of development strategy" *Renewable Energy*, Vol. 33 (2008) 111; Bilgili, "Offshore wind power development in Europe and its comparison with onshore counterpart" *Renewable and Sustainable Energy Reviews*, Vol. 15 (2011), 905.
[77] HELCOM, Planning the Bothnian Sea (2013), 69-70.
[78] Benjamins et al., "Potential environmental impacts of floating solar photovoltaic systems", *Renewable and Sustainable Energy Reviews*, Vol. 199 (2024),6-8.
[79] Hong et al., "Floating offshore wind farm installation, challenges and opportunities: A comprehensive survey", *Ocean Engineering*, Vol. 304 (2024).
[80] Wang, "Maritime Law Enforcement Concerning Offshore Energy Platforms: Navigating International Law Constraints and Challenges", *Marine Policy*, Vol. 170 (2024), 1; Wang et al., "Review of Recent Offshore Photovoltaics Development", *Energies*, Vol. 15, No. 20 (2022), 11; Wu et al., 17.
[81] See, e.g., Goodale et al., "Cumulative adverse effects of offshore wind energy development on wildlife", *Journal of Environmental Planning and Management*, Vol. 59, No. 1 (2014) 1–21.
[82] Caine, "The Race to the Water for Offshore Renewable Energy: Assessing Cumulative and In-combination Impacts for Offshore Renewable Energy Developments" *Journal of Environmental Law*, Vol. 32, No. 1, (2020), 83, 104.
[83] Bennett et al., "The human right to a clean, healthy and sustainable ocean" *npj Ocean Sustainability*, Vol. 3 (2024), 6.

Justice of the EU established that Member States are authorised to use the exemptions for renewable energy for climate and energy purposes when licensing operations. However, the use of such exemptions is contingent on there being no alternatives to satisfy the demands for secure renewable energy deemed to be in *overriding public interest*.[84]

3.2 Wave and tidal energy

The ocean is an immense source of energy that can be extracted in multiple ways, including from tides, waves and currents. Ocean wave energy alone has the potential to meet the global energy demand.[85] The IPCC and IRENA have identified marine renewables as an essential component in the path to decarbonisation and alignment to the 1.5°C Paris Agreement limit, noting also their role in job creation.[86]

Affected by a number of factors – the moon and the sun's gravitational pull, earth's rotation, salinity, and ocean floor and seabed topology – tidal power can be exploited by installing turbines underwater and attaching energy convertors to the seabed or through barrages.[87] Tidal stream energy requires strong winds combined with water depths of twenty to fifty meters, criteria that only few locations meet.[88] Currently, large companies and investors are required for this type of marine energy as the costs are still high and the commercial and technical feasibility is yet to be fully understood.[89]

These types of marine energy may have some negative socio-economic and environmental impacts. However, due to the early stages of the technology of tidal energy, precise impacts are still uncertain. Known environmental impacts include the death, entanglement, and injury of animals due to collision, as well as alteration of habitats and oceanographic processes.[90] Since wave energy is influenced by wind, periods of high-intensity may lead to movements of the seabed, also affecting the transmission of biological elements and the marine environment. The precise impact of converters is still largely unknown: it has been suggested that wave fields would only be marginally affected,[91] while other studies indicate reduced water circulation behind turbines. Collision risks with marine animals appear to be rather low,[92] even though

[84] Art. 4(7) 2000/60/EC Water Framework Directive. See also Suvi-Tuuli Puharinen, "Good Status in the Changing Climate? – Climate Proofing Law on Water Management in the EU", *Sustainability*, Vol. 13, No. 2 (2021) 517.
[85] IPCC (n 6), 649.
[86] IRENA, World Energy Transitions Outlook: 1.5°C Pathway (2021) ; IPCC, Renewable Energy Sources and Climate Change Mitigation — IPCC (2011).
[87] Das Neves, "Offshore Renewable Energy and the Law of the Sea" in Johansen et al. (eds), *The Law of the Sea and Climate Change: Solutions and Constraints* (Cambridge University Press 2020) 210.
[88] Samsó et al., "'Examining the Potential of Marine Renewable Energy: A Net Energy Perspective", *Sustainability*, Vol. 15, No. 8050 (2023) 5.
[89] Das Neves (n 87), 210; Weiss et al., "Marine Renewable Energy Potential: A Global Perspective for Offshore Wind and Wave Exploitation", *Energy Conversion and Management*, Vol. 177, 51.
[90] Salvador et al., "Socio-economic, legal, and political context of offshore renewable energies", *WIREs Energy and Environment*, Vol. 12 (2023), 4.
[91] Cui et al., "Marine Renewable Energy Project: The Environmental Implication and Sustainable Technology", *Ocean & Coastal Management,* Vol. 232 (2023) 2; Ouro et al (n 51), 4.
[92] Ouro et al. (n 51), 7.

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rotors and wires moving at high speeds can pose risks to marine animals, especially near the surface at night.[93]

From a socio-economic perspective, marine energy may restrict Indigenous Peoples' access to marine resources.[94] New development in offshore environments that are already intensely used for aquaculture, fishing transportation or tourism can intensify conflicts between users and complicate the implementation of marine renewable energy.[95] This is especially the case given that marine energy is more suitable and technologically viable when installed close to shore, ports and highly populated areas.[96] Small-scale fishers are especially vulnerable when access to marine spaces is renegotiated.[97]

6. Geothermal energy

The decay of magma and radioactive material leads to the formation of geothermal energy. It is a location-specific energy source that depends on areas with favorable geothermal resources.[98] The potential of geothermal resources is much higher than the global demand for electricity. Yet, due to high upfront costs, decentralized heat production, the variety amongst projects, geological uncertainties and technical risks, only little potential has been developed. New technologies and governance frameworks can support a successful scale-up, while also limiting adverse environmental impacts.[99] After the expensive exploration and installment stages, operation costs fall significantly.[100] Importantly, geothermal energy is barely impacted by fluctuating prices of raw materials or political tensions at the international level.[101] Geothermal energy can directly be used for heating, but also for electricity generation, cooling and aquaculture.[102]

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[93] Hammar et al., "Introducing Ocean Energy Industries to a Busy Marine Environment", *Renewable and Sustainable Energy Reviews,* Vol. 74 (2017), 181.
[94] Kerr et al., "Rights and Ownership in Sea Country: Implications of Marine Renewable Energy for Indigenous and Local Communities", *Marine Policy*, Vol. 52 (2015).
[95] Das Neves (n 87), 213. De Groot et al., "A sea of troubles? Evaluating user conflicts in the development of ocean energy" in Wright et al. (eds.), *Ocean Energy: Governance Challenges for Wave and Tidal Stream Technologies* (1st edn, Routledge 2018) 178-179.
[96] Weiss et al. (n 89), 48-49.
[97] Pomeroy et al., "Power and Perspective: Fisheries and the Ocean Commons Beset by Demands of Development", *Marine Policy*, Bol. 61 (2015) 341, 345.
[98] Xuyang Liu et al., "A survey of geothermal power generation combined with renewable energy for low carbon emissions", *Clean Energy*, Vol. 8 No. 3 (2024) 139.
[99] IPCC (n 6), 648-649.
[100] Abdi et al., "Social acceptance and associated risks of geothermal energy development in East Africa: perspectives from geothermal energy developers", *Clean Energy*, Vol. 8, No. 5 (October 2024) 21-22, 28; Hammons, "Geothermal Power Generation: Global Perspectives; U.S.A. and Iceland; Technology, Direct Uses, Plants, and Drilling", *International Journal of Power & Energy Systems*, Vol. 27, No. 2, (2007) 161, 169; Soltani et al., "Environmental, economic, and social impacts of geothermal energy systems", *Renewable and Sustainable Energy Reviews*, Vol. 140 (2021) 9; Kaczmarczyk et al., "Life Cycle and Water Footprint Assessment in the Geothermal Energy Sector", *Energies*, Vol. 17 (2024) 16.
[101] Kaczmarczyk et al. (n 100), 16.
[102] Abdi et al. (n 100), 28; Xuyang Liu et al. (n 98), 139.

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As the UN Special Rapporteur on Toxics already pointed out, ecological drawbacks of geothermal energy include air and water pollution risks, as most geothermal power plants require a large amount of water for cooling or other purposes and steam released at the surface may contain hydrogen sulfide, ammonia, methane and carbon dioxide. Moreover, dissolved solids discharged from geothermal systems include sulfur, chlorides, silica compounds, vanadium, arsenic, mercury, nickel and other toxic heavy metals (see A/HRC/54/25). Therefore, geothermal power plants can contribute to the pollution of surface waters if geothermal fluids are discharged into surrounding bodies of water. Through the consistent practice of reinjection, harmful discharges can be avoided. Geothermal energy production may also lead to the pollution of ground water if liquids are not properly discharged or if storage ponds are permeable and let liquids seep through. Careful design, quality control and monitoring can prevent such impacts.[103] There have been several reported hydrogen sulphide gas leaks, leading to acute respiratory infections and itching skin, which are attributed to the exposure to sulphur vapours and mud emitted by the geothermal operation. In that context, safety precautions are essential.[104] Even when geothermal plants filter out most of the harmful emissions, they still emit visible haze that largely consists of excess steam. It is important to explain to local communities what the impact is of these emissions are, and how they differ from emissions of fossil fuel plants,[105] and what precautionary and safety measures have been taken to prevent negative impacts on human health and the environment.

As biological, chemical and geological features of geothermal sites can support the development of unique and sensitive ecosystems,[106] geothermal energy resources are often located in national parks or other protected areas with geothermal activity.[107] Deforestation in these areas can disturb hydrological cycles, which risks affecting agricultural irrigation and the recharge of geothermal resource.[108]

Drilling activities required to use geothermal energy can lead to small-scale soil erosion and geological destabilization.[109] Changes in the flows of heat and water can lead to land subsidence, landslides and catastrophic events.[110] While reinjection can reduce the risks of subsidence, areas should be closely monitored.[111] The creation of geothermal facilitates can also increase the frequency of seismic events.[112] Therefore, protocols to manage seismic alerts are crucial.[113]

[103] DiPippo, "Geothermal energy electricity generation and environmental impact", *Energy Policy*, vol. 19, No. 8 (October 1991), 802-803; M. Soltani et al. (n 100), 5.
[104] Submission by PPMAN et al. (Indonesia).
[105] Abdi et al. (n 100), 26-27.
[106] Dhar et al., "Geothermal energy resources: potential environmental impact and land reclamation", *Environment Review*, Vol. 28 (2020) 419.
[107] Soltani et al. (n 100), 2. Submission by PPMAN et al. (Indonesia)
[108] Dhar et al., "Geothermal energy resources: potential environmental impact and land reclamation", *Environment Review*, Vol. 28 (2020) 419-420.
[109] Kaczmarczyk et al. (n 100), 5.
[110] Manzella et al., *Geothermal energy & society*: Springer (2019) 15; Soltani et al. (n 100), 3-4.
[111] Manzella et al. (n 110), 15.
[112] Submission by PPMAN et al (Indonesia).
[113] Manzella et al. (n 110), 15; Soltani et al. (n 100), 3-4.

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System design is crucial in determining the environmental impacts of geothermal energy, and a life cycle assessment is necessary to determine the water footprint of plants, coupled with monitoring of mitigation methods.[114] To mitigate negative ecological effects, developers should avoid sensitive areas, areas of historical significance and areas with exceptional national beauty.[115] Reservoirs can be restored, sites fenced and plants equipped with silencers.[116] It is recommended to restrict temperature changes as much as possible, and to plan and manage the substrate systematically.[117] Microbial control strategies should also be developed.[118]

Lastly, communities often do not participate in decision making on or benefits from geothermal development. Socio-economic exclusion has important implications for access to electricity and social infrastructure,[119] and can also promote a sense of isolation among communities affected by the project.[120] In such cases, geothermal development can exacerbate inequalities.[121] Lack of participation of communities in decision-making also prevents authorities and developers from better understanding potential impacts and co-develop effective preventive measures.

7. Hydropower

Hydropower refers broadly to river water with high potential energy running over turbine blades of various kinds to generate electricity. In the last decade, it remained the predominant source of renewable energy, providing around 15 percent of the world's electricity.[122] It can be used to provide electricity flexibility and store energy, while also being low in cost. To protect its future climate change mitigation potential, however, environmental and social impacts of hydropower should be minimized, while also reducing the risks of dam failures and modernising existing infrastructure.[123] The International Renewable Energy Agency estimates that hydropower capacity may double by 2050 compared to 2022.[124] Prospective capacity of countries to deploy more hydropower is closely monitored.[125] To install new plants, a

[114] Kaczmarczyk et al. (n 100), 6.
[115] Dhar et al. (n 106), 417.
[116] Soltani et al. (n 100), 5.
[117] Griebler et al., "Potential impacts of geothermal energy use and storage of heat on groundwater quality, biodiversity, and ecosystem processes", *Environmental Earth Sciences*, Vol. 75 (2016) 16.
[118] Amundson et al., "Anthropogenic impacts on the terrestrial subsurface biosphere", *Nature Reviews Microbiology*, Vol. 23 (March 2025) 155.
[119] Schade, "EU accountability for the due diligence failures of the European Investment Bank: climate finance and involuntary resettlement in Olkaria, Kenya", *Journal of Human Rights and the Environment*, Vol. 8, No. 1 (March 2017) 77.
[120] Abdi et al. (n 100), 27.
[121] Özen, "Smallholder women rising: Intersectional dynamics of resistance to geothermal energy in Western Turkey", *Energy Research & Social Science*, Vol. 120 (2025) 6-8.
[122] IRENA, Tracking SDG 7: The Energy Progress Report 2025 (2025), 5; see also Ritchie et al., "Renewable Energy", *Our World in Data*, 2020.
[123] IPCC (n 6), 638-639.
[124] IRENA, World Energy Transitions Outlook 2022. 1.5°C Pathway (2022), 67.
[125] Global Energy Monitor, Global Hydropower Tracker Summary Data.

considerable amount of time needs to be taken into account for the construction and the filling of the reservoir.[126]

As hydropower is not weather-dependent like wind or solar power, it provides a stable source of energy that can balance out other more variable sources.[127] That said, the economic and financial viability, efficiency, and carbon reducing potential of hydropower dams is highly questionable, particularly in areas that are vulnerable to climate change and earthquakes. Altered precipitation patterns and variable runoff due to climate change lead to a loss of hydropower output around the world. Extreme weather events that damage dams can also lead to a lower energy output.[128]

Hydropower comes with social and political concerns as well. Much of the currently built and planned dams are on rivers shared between two or more countries, which raises the risk of increased inter-state conflicts. There is also still a need to build participatory processes within river basin organizations to consider impacts on local communities.[129] This is important especially since hydropower development drives environmental, social, and health harms, from community displacement to biodiversity loss due to large dams,[130] which have been documented by UN human rights experts.[131] Over 130 environmental groups have urged the EU not to classify new hydropower as renewable in proposed new legislation.[132]

Globally, large dams have forcibly displaced 40 to 80 million people and severely affected the livelihoods of another 470 million people living downstream.[133] Affected populations report being excluded from direct land compensation, facing severe devaluation of their land, higher costs, and receiving no consideration for lost income from grazing, agriculture, or commercial assets like shops and hotels.[134] The process is often accompanied by lack of culturally appropriate housing in resettlement sites and lack of redress for loss of sacred sites, including inundated burial grounds, temples and important forest and river areas.[135]

Damming has been found to disrupt tourism and recreational activities as well as local people's sense of place. In addition, communities report consistently living in fear of potential dam collapse, especially for dams that are planned in ecologically sensitive areas known to have seismic activity.[136] Moreover, hydropower plants have been linked to an increase in sexual

[126] IPCC (n 6), 639.
[127] Yang et al., "Burden on Hydropower Units for Short-Term Balancing of Renewable Power Systems", *Nature Communications*, Vol. 9 (2018).
[128] IEA, World Energy Outlook 2024 (2023), 233-234.
[129] Hensengerth, "Inclusive governance of hydropower on shared rivers? Toward an international legal geography of the Lower Mekong basin", *Frontiers in Climate,* Vol. 6 (2024), 1.
[130] Submission by GCHA.
[131] Arrojo Agudo et al., Joint statement on the human rights of people affected by dams and other water infrastructure (2021). https://www.un.org/esa/sustdev/sdissues/energy/op/hydro_cernea_social%20impacts_backgroundpaper.pdf
[132] Open letter: Counting on New Hydropower in Europe Is Irresponsible, (6 February 2023).
[133] Submission by Alternative Law Collective et al.
[134] Submission by Alternative Law Collective et al.
[135] Submission by International Rivers.
[136] Submission by International Rivers.

exploitation and abuse, child pregnancy, alcohol and drug consumption among youth, child labour, the breakdown of family and community ties, and the dismantling of health, education, and protection services.[137]

Hydropower often requires river diversion, tunnelling, and construction, all of which reduce water flow, disrupting agriculture, and affecting glacier-fed springs, causing water scarcity and harms to tourism and livelihoods, as well as increasing the risk of water poisoning and liver disease.[138] Hydropower development therefore leads to loss of access to water for nearby communities, and a consequent loss of access to healthy foods once relied upon from river habitats, such as riverweed, fish and other aquatic species, and from cultivated or foraged foods due to inundation.[139] Dam operations can disrupt fish migration patterns, and block sediment that would flow downstream to retain the fertile riverbank areas, which in turn can severely decrease peoples' ability to rely on wild fish catches and riverbank gardens as sources of healthy, plentiful and affordable food year-round.[140] Freshwater ecology and biodiversity have already been adversely affected by human activities globally,[141] but large-scale hydropower causes further impacts, as the ecological cycle of a river depends on the free flow of water. The fragmenting effect of hydropower plants can be mitigated by establishing sediment passes and aids for fish migration.[142]

Large dam construction entails blasting in the mountains to collect construction material and building underground tunnels, which is damaging to the hearing of people in nearby communities. Rock fragments from these blasts have damaged crops and can threaten human lives.[143] Deforestation and biodiversity loss, including fruit and medicinal species, during construction and resettlement directly impact the rights to food and health, as well as livelihoods in terms of loss of rents paid on grazing grounds and payments collected from those harvesting honey, herbs, mushrooms, and medicinal plants.[144]

The contribution of hydropower to climate change mitigation has also been increasingly questioned. The net total carbon emissions of the operation may vary considerably depending on soil composition and the type of hydropower operation.[145] Large-scale hydropower operations in particular, which are based on storing water and regulating river flows and

[137] Oliveira et al., Levando os direitos das crianças e adolescentes a sério: parâmetros e recomendações para os tomadores de decisão envolvidos com obras e empreendimentos, Belém, Snta Cruz (2018); submission by FGV Center for Human Rights and Business.
[138] Submission by Alternative Law Collective et al.
[139] Submission by International Rivers.
[140] Submissions by International Rivers and Children and Youth Major Group to UNEP.
[141] Tockner et al., "Domesticated Ecosystems and Novel Communities: Challenges for the Management of Large Rivers", *Ecohydrology & Hydrobiology*, Vol. 11 (2011); Vörösmarty et al., "Global Threats to Human Water Security and River Biodiversity", *Nature* Vol. 457 (2010); Thieme et al., "Navigating Trade-Offs Between Dams and River Conservation", *Global Sustainability*, Vol. 4 (2021).
[142] IPCC (n 6), 639; IPCC-IPBES (n 22), 56.
[143] Submission by coalition (PPMAN, Indonesia and et).
[144] Submissions by Alternative Law Collective et al. and GHCA.
[145] International Hydropower Association, Carbon emissions from hydropower reservoirs: facts and myths (2021).

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consequently submerging land areas, can cause significant methane emissions.[146] To achieve realistic data, it is crucial to consider the emissions from reservoirs and lost habitat carbon storage, not to overcount the productivity of hydropower electricity generation facilities,[147] and to factor in impacts of climate change on the output.[148] Greenhouse gas emissions at end of life dismantling also need to be factored in.[149] Despite these potential drawbacks and the wide differences among different reservoirs, there is considerable evidence that on global average the emissions from hydropower remain significantly lower than fossil fuels.[150]

Limited research suggests that the emissions reduction can decline over time as the displacement of communities may result in lifestyle changes that are higher in emissions, for example by forcing people to commute to new modes of employment in urban centres.[151] In their early stages, hydropower projects may have GHG emissions levels that come close to natural gas as newly created reservoirs emit GHG through the decomposition of biomass.[152] This is especially the case when the construction requires the flooding of native forests, which are major carbon sinks.[153] Tropical forests, peatlands, and mangroves have the highest carbon stocks per hectare of all natural terrestrial and coastal ecosystems,[154] but are in many cases negatively impacted by changes to river hydrology caused by hydropower projects.[155] The disruption of local ecology and degradation of wetlands can lead to more emissions.[156]

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[146] "Long-term effect of reservoir emissions on the climate is increasingly dominated by methane", *Nature Geoscience*, Vol. 15 (2022).
[147] Kumar et al., "Hydropower" in IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (2011), 5.6.2.
[148] Ibid, 5.10.1; see also UNESCO World Water Assessment Programme (WWAP), The United Nations World Water Development Report 2025, Mountains and water towers, (2025); Capehart, "Drought Diminishes Hydropower Capacity in Western U.S.", *Water Resources Research Center, The University of Arizona*; Grossman et al., "Reservoir evaporation in the western United States: Current science, Challenges, and future needs", *Bulletin of the American Meteorological Society*, Vol. 99 (2018).
[149] Kumar et al. (n 147), 5.6.3.
[150] E.g. see discussion in Pinguelli Rosa et al., "A model for the data extrapolation of greenhouse gas emissions in the Brazilian hydroelectric system", *Environmental Research Letters*, Vol. 11 (2016).
[151] Bhoyar et al., "Understanding the impact of lifestyle on individual carbon-footprint", *Procedia - Social and Behavioral Sciences*, Vol.133 (2014).
[152] Steinhurst et al., Hydropower Greenhouse Gas Emissions. State of the Research, *Synapse Energy Economics* (2012), 20.
[153] IPBES, "Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services", *Nexus Assessment* (2024).
[154] Epple et al., "Managing Ecosystems in the Context of Climate Change Mitigation: A Review of Current Knowledge and Recommendations to Support Ecosystem-Based Mitigation Actions That Look beyond Terrestrial Forests", *CBD Technical Series,* No. 86. (2016).
[155] E.g. the Mekong Delta has seen significant negative impacts on mangrove forests as a result in widespread hydropower development by several countries in the Mekong Basin. Le Huy et al., "The dangers of the construction of hydroelectric dams upstream of the Mekong River adversely effect on the ecosystems and livelihoods of people in the Mekong Delta, Viet Nam", *Environmental Challenges*, Vol. 5, (2021); Soukhaphon et al., "The Impacts of Hydropower Dams in the Mekong River Basin: A Review", *Water*, Vol. 13, No. 3 (2021), 265; Fawthrop, "Death by strangulation? Hydropower threatens to kill the mighty Mekong", The Ecologist (2019).
[156] Angarita et al., "Basin-scale impacts of hydropower development on the Mompós Depression wetlands, Colombia", *Hydrology and Earth System Sciences*, Vol. 22 No. 5 (2018); Arias et al., "Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland", *Ecological Modelling,* Vol. 272 (2014).

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Emissions from decaying materials are particularly high in warm and tropical climates.[157] In some cases discussed in the literature, however, reservoirs became biodiversity hotspots which provided important habitat for wetland species.[158]

Larger scale hydropower is seen as more effective as it results in greater energy production scales per cost ratio and therefore bring greater financial return on investment.[159] They are also more likely to attract international investment, and therefore be accompanied by the higher standards of environmental and human rights impact assessments.[160] There is, however, evidence of failure to properly assess impacts of such projects,[161] and frequent over-estimation of actual power output levels.[162]

Recently, many projects have been developed consisting of small dams rather than one big dam in an attempt to reduce environmental impact.[163] Such smaller scale projects can have lower environmental impacts, but risk causing similar effects when unsuitably sited and poorly coordinated.[164] This could be adequately mitigated by appropriately scoped national and regional policies. They also demonstrate much lower economic, social and community impacts, and are less disruptive to place-based relationships and identities as they usually do not require mass displacement. Small projects are more amenable to community ownership or partial ownership schemes[165] and can return lifetime economic benefits to marginalised communities.

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[157] Kumar et al (n 147), 5.6.4.2 and 5.6.3.2; see also UNESCO, World Water Development Report 2020: Water and Climate Change (2020), 7.3.1.; Deemer et al., "Greenhouse gas emissions from reservoir water surfaces: a new global synthesis", *Bioscience,* Vol. 66.; No. 11 (2016); Räsänen et al., "Greenhouse gas emissions of hydropower in the Mekong River Basin", *Environmental Research Letters*, Vol. 13, No. 3, (2018); Li et al., "The net GHG emissions of the China Three Gorges Reservoir. I. Pre-impoundment GHG inventories and carbon balance", *Journal of Cleaner Production*, Vol. 256 (2020).

[158] Bérubé and Cusson, "The environmental legal and regulatory frameworks. Assessing fairness and efficiency", *Energy Policy*, Vol. 30 (2002).

[159] Castro-Diaz et al., "Impacts of hydropower development on locals' livelihoods in the Global South", *World Development*, Vol. 169 (2023).

[160] E.g. the reference to the influence of the World Bank's involvement in the project in Castro et al., "Examples of coupled human and environmental systems from the extractive industry and hydropower sector interfaces", *PNAS*, Vol. 113, No. 51 (2016), 14529-14530.

[161] E.g. see Castro-Diaz et al. (n 159); Randell, "The short-term impacts of development-induced displacement on wealth and subjective well-being in the Brazilian Amazon", *World Development*, Vol. 87 (2016); Hay et al., "Dam-Induced Displacement and Resettlement: A Literature Review", *FutureDAMS Working Paper 004*. (2019).

[162] Mayer et al., "Pretend participation: Procedural injustices in the Madeira hydroelectric complex", *Global Environmental Change*, Vol. 75 (2022).

[163] IPCC-IPBES (n 22), 56.

[164] E.g. Athayde et al., "Improving policies and instruments to address cumulative impacts of small hydropower in the Amazon", *Energy Policy*, Vol. 132, (2019); Crnobrnja-Isailović, et al., "Small hydropower plants' proliferation would negatively affect local herpetofauna", *Frontiers in Ecology and Evolution*, Vol. 9. (2021); Liu, et al. (eds.), World Small Hydropower Development Report 2019*, United Nations Industrial Development Organization; International Center on Small Hydro Power*.

[165] E.g. Virah-Sawmy and Sturmberg, "Socio-economic and environmental impacts of renewable energy deployments: A review", *Renewable and Sustainable Energy Reviews,* Vol. 207 (2025); Rygg et al., "Is local always best? Social acceptance of small hydropower projects in Norway", *International Journal of Sustainable Energy Planning and Management*, Vol. 31 (2021); Bauwens, "Analyzing the determinants of the size of investments by community renewable energy members: findings and policy implications from Flanders", *Energy Policy*, Vol. 129 (2019); Cowell et al., "Acceptance, acceptability and environmental justice: the role of

They can also provide energy security to isolated and marginalised communities that experience difficulties in accessing national electricity grids or are vulnerable to grid failures.

Negative impacts arise in terms of the human rights to a livelihood, food and water, healthy environment, and adequate housing, as well as cultural, civil and political rights, such as the right to seek information, express opinions, and associate and assemble freely.[166] Over the past decade, there have been hundreds of attacks globally on defenders of human rights, labour, and the environment in the context of renewable energy projects, with the majority related to hydropower projects.[167] Those who seek redress, remedy or better compensation often face threats, intimidation and lethal attacks due to the heavy vested interests of companies involved, backed by powerful state actors. [168]

In contrast, a participatory approach should evaluate, on the basis of the best available science including Indigenous science and local knowledge, the contributions to climate mitigation, electricity generation, water supply, flood and drought management, irrigation, navigation, fisheries, recreational activities and economic growth. [169] The inclusion of landscape design approaches, when combined with strong participatory approaches can help minimise visual impact and significantly improve project acceptability to local communities.[170] There are some small-scale examples of retrofitting to existing hydropower successfully leading to species and habitat restoration,[171] when it is premised on avoiding harm in the first instance, before considering reducing and mitigating unavoidable harms, by expanding the cost/benefit analysis beyond traditional metrics. Regional planning for hydropower on a cooperative river-basin transboundary basis can optimise hydropower and minimise the environmental harms described above.

8. Bioenergy

Bioenergy is a form of renewable energy sourced from biomass, which refers to organic material derived from living or recently living organisms or their waste or residue. It is the largest source of renewable energy globally, making up 50% of the world's renewable energy.[172] It represents almost 90 percent of renewable energy used for transportation,[173] and

community benefits in wind energy development", *Journal of Environmental Planning and Management*, Vol. 54, No. 4 (2011).
[166] Submission by International Campaign for Tibet.
[167] Submission by BHRRC, 2; BHRRC, Attacks against human rights defenders addressing corporate harm continue across the world (2024).
[168] Submission by International Rivers.
[169] The importance of Indigenous knowledge and participation is highlighted in IPCC-IPBES (n 22), 130.
[170] Enserink et al., "To support or oppose renewable energy projects? A systematic literature review on the factors influencing landscape design and social acceptance", *Energy Research & Social Science*, Vol. 91 (2022).
[171] E.g. see the example of Norway in Finserås, "Nature-based solutions in the energy transition: A legal perspective" *RECIEL*, (2025).
[172] IEA, Bioenergy.
[173] IRENA, Tracking SDG 7: The Energy Progress Report 2025 (2025), 69.

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is a valuable energy source for sectors with only limited alternatives to fossil fuels.[174] A tripling of woody biomass supply for energy is expected to occur between 2021 and 2030.[175] A competitive scaling up of bioenergy requires advanced technology, robust business strategies and an optimization of the use of by-products. It is difficult to assess the implications of such a scale-up, however, as it is closely tied to land use by other sectors, such as food production and forestry. While bioenergy holds the potential to actively remove carbon from the atmosphere, large-scale production also risks coming into conflict with other environmental and societal priorities.[176]

There are serious concerns that the supply will be provided by monoculture plantations of up to 13 times current levels, following a previous 50% increase between 2010 and 2021.[177] The most destructive biomass growths for biodiversity appear to be soy bean, wheat, maize and palm oil.[178] In terms of food security,[179] land use decisions must be tailored to local food needs but should prioritise food security over biomass to ensure sustenance.[180] Initially intended to provide robust regulatory incentives for the adoption of biofuels, policy initiatives intended to set up sustainability criteria or safeguards are considered to have 'badly faltered' and transformed into burdensome attempts to rectify previous errors.[181]

Plantations increase the risk of nutrient loss and pollution in groundwater, and impact forest species diversity.[182] The UN Special Rapporteur on Toxics already underscored that biofuel production can be water- and land-intensive, and that it relies on raw materials that require fertilizers for their production, the overuse of which may cause water contamination (see A/HRC/54/25). Plantations can also lead to impacts on land-use and biodiversity, by negatively affecting water availability, soil fertility, fire frequency and the availability of medicinal plants, all of which disproportionately impacts Indigenous women.[183] In Indigenous territories, biomass production has led to the loss of forest food, medicine, and traditionally used building materials.[184] In Saami territories, the cumulative effects of forest biomass extraction and plantations significantly reduced the availability of lichens and other ground vegetation essential for reindeer grazing, especially during winter. They also introduced physical barriers that restrict traditional migratory routes and limit the herd's movement across the landscape.[185]

[174] IPCC (n 6), 643.
[175] Biomass Action Network, Burning Up the Biosphere: A Global Threat Map of Biomass Energy Development, 2024 update (2024).
[176] IPCC (n 6), 643-645.
[177] Submission by BAN.
[178] Tudge et al., "The impacts of biofuel crops on local biodiversity: a global synthesis", *Biodiversity and Conservation*, Vol. 30, No. 11 (2021).
[179] Da Cunha Dias et al., "Global potential assessment of available land for bioenergy projects in 2050 within food security limits", *Land Use Policy*, Vol. 105 (2021).
[180] Muscat et al., "The battle for biomass: A systematic review of food-feed-fuel competition", *Global Food Security*, Vol. 25 (2020).
[181] Fairley, "The biofuel course correction", *Nature,* Vol. 611 (2022).
[182] Wu et al., "Bioenergy production and environmental impacts", *Geoscience letters*, Vol. 5 (2018), 3-5.
[183] Submission by BAN; see also IPCC-IPBES, Co-sponsored workshop report on biodiversity and climate change (2021), 53.
[184] Submissions by PPMAN et al (Indonesia) and Forest Watch Indonesia.
[185] Submission by Saami Council.

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When deployed at a small scale, however, bioenergy crops can contribute to the restoration of degraded areas and promote biodiversity. Perennial crops can contribute to landscape heterogeneity and habitat diversity.[186]

Bioelectricity can mitigate greenhouse gas emissions when compared to electricity derived from fossil fuels, especially in areas or countries with diverse biomass.[187] However, the rise of electric vehicles raises questions about biofuel's long-term role in transport.[188] Biofuels also show potential for GHG mitigation in shipping,[189] and aviation.[190] However, high costs currently limit uptake.[191]

In terms of human rights impacts, forest biomass energy emits even more toxic pollutants than fossil fuels, including nitrogen oxides, volatile organic compounds, ammonia, sulphur dioxide, and particulate matter.[192] Bioenergy production, including the handling and combustion of biomass, can expose workers to dust and smoke which increases respiratory risks.[193] There are serious adverse health effects associated with the manufacturing of wood pellets. Exposure to chemicals has been shown to lead to respiratory illnesses, heart disease, premature deaths, low birth rates, type 2 diabetes, strokes, Alzheimer's, Parkinson's, and lung, kidney, and bladder cancer.[194]

Health effects associated with the manufacturing of wood pellets appear to disproportionately imperil poor populations, mostly communities of colour. Many of these chemicals are extremely combustible, putting poor communities at greater risk of explosions and fires. They are also experiencing exacerbated flooding from the clear-cutting, along with toxic, industrial groundwater contamination.[195] Often there are little to no benefits shared with communities, not even in terms of access to energy when crops are exported.[196] The expansion of bioenergy sectors has disproportionately benefited large companies while marginalising local and traditional communities through poor labour conditions, exclusionary governance, and a lack

[186] IPCC-IPBES (n 22), 53.
[187] Erdinc Ersoy and Ugurlu, "Bioenergy's role in achieving a low-carbon electricity future: A case of Türkiye", *Applied Energy*, Vol. 372 (2024).
[188] Poggio et al., "The role of bioenergy in Brazil's low-carbon future", *Energy and Climate Change,* Vol. 5 (2024); Aguiar et al.
[189] Djun Barbosa Watanabe et al., "Climate change mitigation of drop-in biofuels for deep-sea shipping under a prospective life-cycle assessment", *Journal of Cleaner Production*, Vol. 364 (2022).
[190] O'Connell et al., "Considerations on GHG emissions and energy balances of promising aviation biofuel pathways'", *RSER*, Vol. 101 (2019); Wise et al., "Biojet fuels and emissions mitigation in aviation: An integrated assessment modelling analysis", *Transportation Research*, Vol. 52(A) (2017).
[191] Jaume et al., "Evaluating the impact of the new environmental regulations on airlines' business results", *Aircraft Engineering and Aerospace Technology*, Vol. 97, No. 1 (2024); Oesingmann, 'The Economic Impacts of EU Climate Policies on Intra-European Aviation' in Demir et al. (eds) *Eurasian Business and Economics Perspectives* (Springer 2023).
[192] Submission by EEECHO and others.
[193] Submission by GHCA.
[194] Submission by BAN.
[195] Submission by Greater Greener Gloster, EEECHO, Dogwood Alliance, PPMAN et al (Indonesia).
[196] Submission by BAN; Refani and Putra, Borneo forest's silent sacrifice: Japan's Energy Transition and the Shadow of Indonesia Illegal Biomass Trade, *EPN report* (2024).

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of accountability.[197] This includes indications of forced labour, child labour and unsafe working conditions.[198]

From a climate mitigation perspective, systematic reviews often point out the discrepancies among literature on carbon neutrality.[199] While most studies account for direct GHG emissions from cultivating and processing, many early studies omit land use change from calculations, resulting in overestimated mitigation potential.[200] Biomass can be a high-carbon-emitting source that is collected and burned at a more rapid rate than it is replaced. The carbon dioxide released per unit of heat produced during combustion is greater for woody biomass than for coal. When woody biomass is used solely or in combination with coal to produce electricity, the efficiency of electricity production is lower than coal. Hence, the amount of carbon dioxide released per unit of electricity produced by woody biomass is typically 50% greater than coal. While it is possible to maintain a constant amount of carbon in the forest by burning trees at the growth replacement rate of the total forest, there is always more carbon dioxide in the atmosphere than there would have been had the trees not burned. The use of fossil fuels to cut, chip, pelletize, dry and transport wood pellets to their combustion site is estimated to account for 15- 20% of the embedded biomass energy.[201] Furthermore, a growing body of research reveals that forests interact with the atmosphere in many ways other than through the global carbon cycle, affecting rainfall and temperatures from global to local scales. Forests' non-carbon effects are essential for fighting climate change, for food and water security, human health and climate resilience.[202]

Second generation biofuels – which are created from non-food biomass including agricultural residue,[203] grasses and straw,[204] forest waste, lignocellulosic wastes (the structural component of plant cell walls),[205] or inedible oils such as jatropha[206] – can be grown on marginal land rather than agricultural land.[207] Second-generation bioenergy from agricultural residues, especially sugar beet or cane, generally has a lower water footprint than first generation

[197] Bastos Lima, "Just transition towards a bioeconomy: Four dimensions in Brazil, India and Indonesia", *Forest Policy and Economics*, Vol. 136 (2022).
[198] Submission by FGV Center for Human Rights and Business; BHRRC, Renewable Energy Risking Rights & Returns: An analysis of solar, bioenergy and geothermal companies' human rights commitments (2018), 17.
[199] Pandey and Erbaugh, "Driving sustainable uptake: a systematic review of global literature on policies governing woody biomass for energy", *Discover Sustainability*, Vol. 5, No. 28 (2024).
[200] Reid et al., The future of bioenergy, Global Change Biology, Vol. 26, No. 1 (2019).
[201] Moomaw, Myth of Carbon Neutrality of Biomass, *EPN fact sheet* (2020).
[202] Ellison et al., "Trees, forests and water: Cool insights for a hot world", *Global Environmental Change*, Vol. 43 (2017).
[203] Duque-Acevedo et .al, "The Management of Agricultural Waste Biomass in the Framework of Circular Economy and Bioeconomy: An Opportunity for Greenhouse Agriculture in Southeast Spain", *Agronomy*, Vol. 10, No. 4 (2020).
[204] Padder et al., "Biofuel generations: New insights into challenges and opportunities in their microbe-derived industrial production", *Biomass and Bioenergy*, Vol. 185 (2024).
[205] Ganguly et al., "The second- and third- generation biofuel technologies: comparative perspectives" in Dutta and Mustansar Hussain (eds.) *Sustainable Fuel Technologies Handbook,* Elsevier (2020).
[206] Cavelius et al., "The potential of biofuels from first to fourth generation" *PLOS Biology*, Vol. 21, No. 3 (2023).
[207] Basili and Fontini, "Biofuel from Jatropha curcas: Environmental sustainability and option value", *Ecological Economics*, Vol. 78 (2012); Núñez-Regueiro et al, "Effects of bioenergy on biodiversity arising from land-use change and crop type", *Conservation Biology*, Vol. 35, No. 1 (2019).

crops.[208] Emerging scholarship highlights a potential for crop straw to reduce water usage and irrigation and mitigate GHG.[209] Second-generation bioenergy produced from crops after they have already been used for food has been suggested to mitigate food-energy competition.[210] However, costs can be a barrier as complex feedstocks (such as lignin) require extensive pretreatment.[211] There is also only a limited availability of second-generation biomass, which means that it could not realistically meet the global supply demand on its own.[212] Compared to first generation, second generation is less harmful to biodiversity, while still having a significant impact as a result of which long-term impact remains uncertain.[213]

Third-generation approaches to bioenergy such as microalgal production systems are considered a promising alternative with potentially fewer environmental impacts, as they may generate fewer pressures on biodiversity per unit of fuel generated in the future, mainly because of reductions in direct and indirect land-use change, water consumption if water is recycled and no application of pesticides. However, further improvements in technologies and production methods are still required to scale up techniques at a reasonable cost.[214] There is also the potential for carbon-negative production of bioenergy due to their potential for carbon capture and the absorption of industrial carbon dioxide.[215]

9. Reliance on transition minerals

7.1 Demand for transition minerals

Wind energy and some types of solar energy have relatively light resource footprints.[216] Alternatives to lithium-ion batteries are becoming increasingly feasible and practical, which makes batteries less dependent on traditional critical materials.[217] Photovoltaics rely on a range of raw materials that are generally widely available, substitutable and recyclable. Photovoltaics rely primarily on silicon, copper, glass, aluminium and silver, which are not considered very

[208] Mathioudakis et al.,"The water footprint of second-generation bioenergy: A comparison of biomass feedstocks and conversion techniques", *Journal of Cleaner Production*, Vol. 148 (2017).
[209] Fang et al., "Sustainable energy development of crop straw in five southern provinces of China: Bioenergy production, land and water saving potential", *Renewable Energy*, Vol. 224 (2024).
[210] Muscat et al. (n 180).
[211] Igwebuike et al., "Renewable Energy Potential: Second Generation Biomass as a Feedstock for Bioethanol Production", *Molecules* Vol. 29, No.7 (2024).; Ge et al., "Modelling and economic optimization of cellulosic biofuel supply chain considering multiple conversion pathways" *Applied Energy*, Vol. 281 (2021); Ghaderi et al., "Biomass supply chain network design: An optimization-oriented review and analysis", Industrial Crops and Products, Vol. 94 (2016).
[212] Cavelius et al. (n 206)
[213] Tudge et al., "The impacts of biofuel crops on local biodiversity: a global synthesis", *Biodiversity and Conservation*, Vol. 30, No. 11 (2021).
[214] Alaswad et al., "Technologies and developments of third generation biofuel production", *Renewable and Sustainable Energy Reviews,* Vol. 51 (2015); see also Padder et al. (n 204); Cavelius et al. (n 206).
[215] Padder et al. (n 204).
[216] Bruyninckx et al., 138.
[217] IPCC (n 6), 637.

critical or potentially scarce. After a lifetime of around 30 years, nearly all valuable materials from PV modules can be recycled, preventing toxic contamination and avoiding the accumulation of waste. In addition to all of this, alternative PV materials are becoming more efficient and stable.[218] Similarly, even though wind turbines with permanent magnets rely on rare earth minerals,[219] it is possible to manufacture them without magnets. The downside is that those designs increase the production costs and reduce the efficiency of the turbines.[220]

Projections by the International Energy Agency (IEA) estimate that the global growth in demand for critical minerals by 2040 could be up to six times the current levels.[221] The World Bank estimates that the energy transition could drive a major increase in mineral production by 2050—up to 500% for key battery minerals.[222]

The assessment of criticality of raw materials is not standardized, however, as they are defined differently by different countries.[223] The Organisation for Economic Cooperation and Development (OECD) defines critical raw materials as those raw materials which are characterized both by a high supply risk and a high vulnerability to restriction on the supply. Some studies add a dimension of environmental implications of extraction and use.[224] The economic importance of the materials, especially if their unique properties make them irreplaceable, is also an important indicator of criticality.[225] Although sourced from various locations globally, critical materials and their procurement are concentrated in certain countries and regions. Geographical dependencies can lead to over-reliance, as a result of which a disruption such as political disturbances may undermine the entire supply chain.[226]

Multiple key technologies in different sectors depend on critical minerals. These sectors include communication, aerospace and defence with applications ranging from robotics over digital technologies to drones. Many of the materials are also used intensely for the green transition in wind turbine generators, photovoltaics, lithium-ion batteries and e-mobility.[227]

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[218] Ibid, 632-633.
[219] Buchmayr et al., "Exploring the global and local social sustainability of wind energy technologies: an application of a social impact assessment framework", *Applied Energy*, Vol. 312 (2022) 3.
[220] IPCC (n 6), 638.
[221] IEA (2021), 5.
[222] World Bank, Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition (2020) 93.
[223] Su et al., "Global Dynamics and Reflections on Critical Minerals", *E3S Web of Conferences*, Vol. 352 (2022), 1–3; UNECE, Critical Minerals for the Sustainable Energy Transition. A Guidebook to Support Intergenerational Action (2024) 17.
[224] Coulomb et al., "Critical Minerals Today and in 2030: An Analysis for OECD Countries", *OECD Environment Working Papers No. 91* (2015), 11; UNECE, 18.
[225] UNECE (n 224), 17-18; see also European Commission, Proposal for a Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020, COM(2023)160, 1; Goswami; "Chipping in: Critical minerals for semiconductor manufacturing in the U.S.", *MIT Science Policy Review*, Vol. 4 (2023), 118.
[226] European Commission, *A Secure and Sustainable Supply of Critical Raw Materials in Support of the Twin Transition*, COM(2023)165, 1.
[227] Kowalski and Legendre, *Raw Materials Critical for the Green Transition: Production, International Trade and Export Restrictions*, OECD Trade Policy Paper 269 (OECD Publishing), 11; European Commission; Critical raw materials for strategic technologies and sectors in the EU. A foresight Study (2020).

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Key components that rely on these minerals include batteries, inverters, transformers, mounting frames, cables and wires.[228]

Most existing demand models were developed either to assess potential supply shortages, often with reference to energy security, or to calculate the investment required to scale up production.[229] These projections now inform infrastructure planning, trade and investment policy, and raw materials diplomacy at both national and multilateral levels. They are widely referenced by institutions such as the IEA, IRENA, and the European Commission.

In practice, high-demand scenarios are frequently cited in planning documents and public strategies that anticipate or call for expanded extractive activity. Given the environmental and social implications of increased mining, there is a growing recognition of the need to scrutinize how demand estimates are constructed. Recent research has shown that projections can vary significantly depending on modelling assumptions, the treatment of recycling and substitution, and expectations around technological development. This variability raises questions not only about methodological choices, but also about how demand forecasts are used to inform policy.

A recent meta-analysis shows that if all models predict a surge in demand for critical minerals in the coming decades, there is such a strong diversity in how models are created that almost all studies disagree on the scale, timeline and rate of demand increase: one study can predict a tenfold increase of the demand for a mineral compared to 2020 levels, when another can predict 100 times increase.[230] For instance, predictions for annual demand for cobalt in 2050 ranges from 6,000 to 3,600,000 tons, with a standard deviation of 880,000 tons.

Demand estimates depend on assumptions about which sub-technologies or type of equipment will be deployed. These choices depend heavily on what is popular or cost-effective at the moment the demand model is built, or based on an assumption about what will be popular or cost-effective in the future. Estimates of how much mineral is required per unit of technology across its lifetime vary widely across studies depending on what sources are used and what modelers prioritize. Wind turbines might require one, two, three, or ten tons of copper and building a single battery EV could require between 600 to 15,000g of lithium and between 700 to 7000g of cobalt depending on the study.[231]

Dynamic variables refer to factors that evolve over time and can significantly alter projections of critical mineral demand. These include recycling rates, changes in energy intensity across the supply chain, policy shifts, and non-energy-related demand drivers. While some models attempt to account for these variables, most rely on static inputs and assumptions, limiting their

[228] IEA, *The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions* (2021), 5.
[229] Bernal et al. "Latin America's Opportunity in Critical Minerals for the Clean Energy Transition." *International Energy Agency*, 7 Apr. 2023, https://www.iea.org/commentaries/latin-americas-opportunity-in-critical-minerals-for-the-clean-energy-transition
[230] Calderon and others, "Critical mineral demand estimates for low-carbon technologies: what do they tell us and how can they evolve?", *Renewable and Sustainable Energy Reviews*, vol. 189 (January 2024).
[231] Liang et al. "Material Requirements for Low-Carbon Energy Technologies: A Quantitative Review." *Renewable and Sustainable Energy Reviews*, vol. 161, 2022, article no. 112334,

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capacity to capture systemic change. As a result, this is where some of the most persistent blind spots in current demand modeling can be found

Recycling assumptions are among the most variable inputs across models, as high-recycling scenarios can reduce primary demand considerably. Valero (2018) provides one of the few estimates of how recycling rates might evolve to 2050,[232] and UNEP's International Resources Panel (2011) remains the baseline for current recycling performance. Yet, there is no standardized methodology for integrating these rates.[233] Differences between closed-loop and open-loop systems, assumptions around collection and recovery efficiency, and the presence (or absence) of economic incentives all shape projections.
The energy intensity of recycling is another underexplored factor. While recycling is often portrayed as a sustainable solution, the process itself is energy-intensive and difficult to decarbonize. The production and refining of critical minerals, especially when sourced as companions or by-products of other ores, requires high energy input,[234] and many of these materials have extremely low end-of-life recycling rates.[235] Few models account for how the energy used in recycling will be sourced.

The widespread adoption of circular economy principles through product redesign, reuse, longer lifespans, and material substitution, has the potential to significantly reduce future demand for primary minerals. UNEP (2020) underlines this potential but notes that few national policies currently translate this vision into concrete targets or mandates. In most models, such systemic transformations are either absent or treated as marginal adjustments, despite their potential to shift overall trajectories.

Often framed through the energy transition, the demand for critical minerals is also driven by industrial endeavors such as advanced microchips, cutting-edge electronics, and defense hardware.[236] In the aerospace and defence sectors, the ongoing demand for titanium metal is substantial: about 81 000 tonnes of titanium is currently embedded in NATO fleets of aircraft and battle tanks as of 2022. In 2019, aerospace applications, in particular aircraft manufacturing, used about two thirds of the available titanium metal supplies in the EU.[237]

Against this background, it should be stressed that forecasting critical mineral demand is marked by deep uncertainty, both in model parameters and in broader socio-political developments. A key source of variability lies in technological processes. This mirrors long-standing critiques of energy forecasting. Despite these limitations, such forecasts remain central to public policy and investment planning. There is growing interest in more adaptive

[232] Valero et al. "Material Bottlenecks in the Future Development of Green Technologies." *Renewable and Sustainable Energy Reviews*, vol. 93, Oct. 2018, pp. 178–200
[233] Calderon et al. (n 230).
[234] Sovacool et al. "Sustainable minerals and metals for a low-carbon future." *Science* 367.6473 (2020): 30-33
[235] Nassar et al. "By-Product Metals Are Technologically Essential but Have Problematic Supply." *Science Advances*, vol. 1, no. 3, 2015, e1400180.
[236] United Nations, Department of Economic and Social Affairs (UNDESA). "Harnessing the Potential of Critical Minerals for Sustainable Development." *World Economic Situation and Prospects 2025*, Jan. 2025
[237] Foresight Study from the EU « Critical Raw Materials for Strategic Technologies and Sectors in the EU » (2023).

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modeling approaches that better reflect the pace and complexity of change, as exemplified by the recent launch of the IEA Critical Minerals Data Explorer (updated May 2025). This more flexible framework presents global demand projections for 37 critical minerals across three core scenarios and 11 technology-specific use cases (to be expanded), allowing for more granular, dynamic, and policy-relevant analysis.

Technological uncertainty is a key variable affecting critical mineral demand projections, with implications across all modeling parameters, particularly those relating to technology choices and material intensities, but also energy scenarios which are regularly updated to reflect real-world developments. However, most models continue to rely on static assumptions that underrepresent the disruptive potential of innovation.

Recent literature calls attention to the risks of overlooking technological change. UNCTAD published a comprehensive analysis of how advances in battery chemistry, such as the development of sodium-ion and low-cobalt lithium-ion alternatives, could significantly reshape demand patterns for critical minerals.[238] Similarly, a comparative review of raw material requirement models for low-carbon technologies, warn that many existing assessments fail to include dynamic variables, including technological change. They argue that models relying on fixed inputs for material intensity or market share are likely to "lead to a false estimation of future materials demand", and recommend the adoption of adaptive approaches using time-sensitive data or linear trends based on historical trajectories.[239]

The following cases, based on the World Economic Forum "Top 10 Emerging Technologies of 2025" report, illustrate how technology developments can alter mineral demand projections if scaled. The technologies described below are in varying stages of research, development, and deployment. This anticipatory approach underscores the need for flexible and adaptive demand models that can accommodate rapid technological shifts.

- Structural Battery Composites (SBCs): SBCs are multifunctional materials that store energy like conventional batteries while also serving as structural elements in vehicles or devices. Originally developed by U.S. military labs, they are now being explored for applications in electric vehicles (EVs) and aerospace systems, with key components including carbon fiber and epoxy resin. By embedding energy storage into structural components, SBCs reduce overall system weight. According to the U.S. Department of Energy, a 10% reduction in vehicle weight could yield a 6–8% improvement in fuel efficiency and increase EV range by up to 70%.[240] This shift would reduce reliance on minerals such as lithium, cobalt, and nickel, while diversifying energy storage technologies. The technology remains at an early stage, with challenges including recyclability of carbon fiber and cost efficiency. Still, advances in AI-driven composite

[238] United Nations Trade and Development (UNCTAD). "Changing Battery Chemistries and Implications for Critical Minerals Supply Chains." (2025)
[239] Schulze et al. "Overcoming the Challenges of Assessing the Global Raw Material Demand of Future Energy Systems." *Resources, Conservation and Recycling*, vol. 196, 2024, p. 106054. ScienceDirect.
[240] Nie et al. "Multifunctional Composite Designs for Structural Energy Storage." *Battery Energy*, vol. 2, no. 6, 2023, https://doi.org/10.1002/bte2.20230023.

design may accelerate development of bio-based alternatives.[241] If deployed widely, SBCs could transform both energy storage and transport sectors, easing demand pressure on key battery minerals.

- Osmotic Power: Osmotic power systems generate electricity by exploiting salinity gradients between freshwater and saltwater sources. Two main methods are in development: pressure retarded osmosis and reverse electrodialysis, both of which convert the chemical potential of saltwater mixing into usable energy via specialized membranes. Early commercial projects are already underway in France and Denmark. The technology provides steady, renewable, and low-impact power. It is particularly attractive in hybrid configurations that integrate wind, solar, and hydropower. In addition to power generation, osmotic systems can be coupled with desalination or wastewater treatment to recover critical materials such as lithium and nitrogen. While osmotic power systems do not require large quantities of conventional critical minerals, their contribution to grid resilience could reduce dependence on mineral-intensive energy storage. Furthermore, their potential to support mineral recovery from saline waste streams could create new supply channels, helping to reduce demand for primary extraction.

7.2 Environmental and social impacts of mining

This expansion of the industry raises concerns, as the supply chain of critical minerals has been linked to severe human rights violations. In ten years, the Transition Minerals Tracker recorded hundreds of allegations of thousands infringements in the mining of seven energy transition minerals. Over half of those allegations involve ten companies.[242] The majority of incidents of violence and protests are occurring in countries where transition minerals are extracted: between 2021 and 2023, their extraction was linked to over three hundred incidents of violence or protest.[243]

Forced evictions and relocations happen frequently in the context of mining. These practices can violate human rights, especially if it concerns Indigenous peoples who derive their livelihood from biodiversity services.[244] The creation of precarious wage labour markets, which generally offer local populations unskilled and unstable work options, puts populations at constant risk of geographical or economic displacement exacerbated by a lack of compensation and economic remediation of the socio-environmental impacts associated with mining.[245] There are also serious concerns about forced labor. In the Uyghur Region, Uyghurs and other Turkic and Muslim people have been subjected to arbitrary detention, forced labour and other forms of modern slavery by Chinese authorities in connection to the production of

[241] Ziemińska-Stolarska et al. "A Review of End-of-Life Scenarios for Fibre-Reinforced Polymer Materials." *Energies*, vol. 17, no. 15, 2024, article 3713, https://doi.org/10.3390/en17153713.
[242] Submission by Landesa and the International Land Coalition.
[243] Submission by Alianza por los Humedales Andinos.
[244] Ayuk et al., "Mineral Resource Governance in the 21st Century", *International Resource Panel* (2020), 146.
[245] Submission by Alianza por los Humedales Andinos

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PV.[246] There are increasing concerns about human rights abuses of these groups in other regions of China, as poverty alleviation programmes targeting poor Chinese citizens and other ethnic or politically repressed minorities, include forced separation from their families and confinement of children in orphan camps.[247]

In global supply chains, workers often face exploitative conditions consisting of precarious and dangerous working conditions, including low wages, inadequate safety protections, and severe exposure to toxic substances. All of this threatens the right to freedom from forced labour and the right to safe and decent work.[248]

Child labour and instances of modern slavery are still widespread in the mining industry.[249] While mining may appear to be a tool to lift communities out of poverty, it restricts communities from diversifying their income, and binds them to a deadly source of income.[250] It can disrupt traditional livelihoods and create economic inequalities within communities that cause social disharmony.[251] Third-party recruitment agencies often source and manage low-skilled workforces for transportation, which increases the risks of forced labour, poor working conditions, occupational and safety issues, restrictions on freedom of association for migrant and posted workers, and a lack of effective grievance mechanisms for workers and communities. Constant attention is required to measure sub-contractor due diligence.[252]

Different environmental issues stem from competition for surface water and ground water.[253] Mining can spark habitat clearances[254] or may be accompanied by large-scale deforestation, pollution of freshwater sources due to sedimentation, and associated increases in flooding. With this come health problems including respiratory illnesses, diarrhoea, bronchitis, and contact dermatitis, and the destruction of traditional livelihoods.[255] Especially Indigenous Peoples, have been harmed by mining practices that create air, water, and soil contamination from toxic waste. This has resulted in serious health effects that include dermatological diseases, and cancer. [256] Respect for Indigenous Peoples' human rights is essential considering that more than 50% of tranisiton minerals are estimated to be found in Indigenous territories.[257]

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[246] Submission by Anti-Slavery International; Contemporary forms of slavery affecting persons belonging to ethnic, religious and linguistic minority communities Report of the Special Rapporteur on contemporary forms of slavery, including its causes and consequences, Tomoya Obokata, (A/HRC/51/26) (2022) 6-7.
[247] Berg et al., "Human rights and solar energy. A primer for the Danish solar energy sector", *Report of the Danish Institute for Human Rights* (2025); OHCHR Assessment of human rights concerns in the Xinjiang Uyghur Autonomous Region, People's Republic of China (2022).
[248] Submission by GHCA; Berg et al (n 247) 16.
[249] Ibid.; Sovacool et al., "The decarbonisation divide: Contextualizing landscapes of low-carbon exploitation and toxicity in Africa", *Global Environmental Change*, Vol. 60 (2020b) 13-14.
[250] Sovacool et al. (n 249), 10.
[251] Ayuk et al. (n 244), 145-146.
[252] Berg et al (n 247).
[253] Ayuk et al. (n 244), 134.
[254] Ibid, 140.
[255] Submission by PPMAN et al.
[256] Submission by BHRRC-Colombia.
[257] Owen et al, Energy transition minerals and their intersection with land-connected peoples, (2022) Nature Sustainability.

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The toxics also affect fisheries and animal habitats downstream, including marine environments.[258]The negative environmental impacts can lead to the destruction of carbon sinks, which negatively effects climate change. As available mineral deposits are found deeper and deeper in the earth, the climate footprint of the industry increases.[259]

In cobalt mines in the Democratic Republic of Congo, reports have documented child labour, hazardous working conditions, and extreme poverty, despite the country supplying over sixty percent of the world's cobalt.[260] The United Nations Group of Experts on the DRC has documented the systematic use of forced labour by armed groups and informal mining cooperatives, who coerce miners through threats of violence, debt bondage, and extortion.[261]

Nickel mining in Indonesia has caused toxic pollution, land degradation, and cultural loss for Indigenous communities, who were not consulted prior to project development.[262] Residents living near nickel mines report respiratory and skin disease, headaches, urinary tract infections, and eye irritation.[263] Companies employ in-situ leaching with strong acids that poison soil and water. Villagers report that rivers no longer contain fish and that stepping into water causes skin infections, while livestock dies from contaminated streams.[264]

Lithium extraction in the South American Lithium Triangle has led to serious and increasing water depletion, compromising both ecosystems and the livelihoods of Indigenous communities dependent on wetlands and groundwater. Its excessive use of water, exacerbating the water stress of salt flats has given it the name "hydrological mega-mining".[265] The decline in aquifer levels and the drying up of floodplains is seriously threatening the right to water of Indigenous peoples in the Gran Atacama. It affects the availability of plant fibers for the production of wool and textiles, plants and animals for human consumption, and pastures for sheep and llamas. The construction of roads, evaporation wells, processing plants, and camps has directly affected the landscape, the communities' way of life, and their heritage since, in many cases, it involves encroachment on titled territories, affecting the cultural relationship between people and the land. Mining has caused a breakdown in the social fabric, internal divisions due to the dynamics of government and corporate intervention, and violations of the rights of Indigenous peoples to their own forms of government and representation.[266]

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[258] Ayuk et al. (n 244), 134-137.
[259] Ibid, 143.
[260] Submission by SIRGE; Andreoni and Avenyo, Critical Minerals and Routes to Diversification in Africa: Opportunities for diversification into Mobile Phone Technologies - The Case of Democratic Republic of Congo, *background paper commissioned by the UNCTAD secretariat* (2023), 5.
[261] Submission by CIDSE.
[262] Submission by SIRGE; Lo et al., "Nickel mining reduced forest cover in Indonesia but had mixed outcomes for well-being", *One Earth*, Vol. 7, No.11 (2024).
[263] Submission by Amnesty International.
[264] Submission by Dharmesh Shah.
[265] Submission by Climate Law in International Context; Wetlands International, World Water Day: The water impacts of lithium extraction (2023).
[266] Submission by Alianza por los Humedales Andinos.

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In British Columbia, copper mine tailings dam failure has resulted in long-term impacts on the watershed. The responsible actor did not pay the full costs of the clean up and was permitted to discharge mine effluent into a nearby lake, raising concerns about long-term health impacts for residents.[267]

7.3 Waste production and recycling

At the stage of mine decommissioning, failures to adequately rehabilitate a project site and properly restore tenure rights to local communities can result in several adverse human rights impacts. Inadequate handling and disposal of decommissioned solar technology waste pose environment-related human rights risks as they may release toxic waste such as lead or cadmium. This can result in the contamination of air, soil and water, and affect communities' and workers' health. [268] Abandoned extraction sites leave long-term environmental and health hazards, including soil contamination, groundwater pollution, and ecosystem degradation.[269] The storage of tailings exposes communities and workers to significant safety risks that require continuous risk mitigation efforts.[270] Long neglected in governance, the environmental and social impacts after mining closure should be considered during the development process.[271]

At the end of their life, solar panels themselves also generate large amounts of waste. In the face of those large quantities, the solar industry is considered to be unprepared for the challenge as economic incentives seem to encourage landfill disposal over recycling.[272] The phenomenon of 'early retirement' contributes to the high volume of e-waste, as individual households might be incentivized to replace their solar panels early when better performing systems become available.[273] IRENA estimates that global End-of-Life panels could reach 78 million metric tons by 2050. With most predicted to be unrecycled, this significantly increases the risk of toxic contamination in communities near waste dumping sites, leading to land-use inefficiencies and harm to local ecosystems.[274] Estimates predict that solar panels will make up a large part of future global e-waste streams. The e-waste will be a burden to future generations, especially if not handled carefully.[275] Similarly, most EV batteries in the market are not designed for repair, as they have proprietary parts and disassembly procedures specific to the manufacturer to maintain competitive advantage against other manufacturers. If the product cannot be repaired, the product becomes hazardous waste and contributes to waste colonialism, as there is often no domestic capacity to safely dispose of the waste. [276]

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[267] Submission by Amnesty International.
[268] Berg et al (n 247).
[269] Submission by GHCA.
[270] Submission by Greenpeace.
[271] Ayuk et al. (N 244), 133.
[272] Sovacool et al. (n 249), 8.
[273] Mulvaney, "Opening the Black Box of Solar Energy Technologies: Exploring Tensions Between Innovation and Environmental Justice", *Science as Culture*, Vol. 22, No. 2 (2013) 10.
[274] IRENA, End-of-life management: Solar Photovoltaic Panels (2016), 20.
[275] Sovacool et al. (n 249), 10; IPCC (2022) 633.
[276] Submission by Global Alliance on Incinerator Alternatives (Asia- Pacific).

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A lack of recycling policies, capacity or technology can lead to the improper handling of renewable energy wastes. When this happens, the disposal of renewable energy technologies creates serious environmental and health risks, as hazardous materials such as cadmium, lead, chromium, tellurium, and fluorine-based compounds might leach into the soil and water.[277] Downstream toxic waste is often exported to lower-income countries that lack sufficient waste management infrastructure.[278] This violates communities' right to a clean, healthy and sustainable environment.[279] Marginalised populations living near landfills are disproportionately affected, especially when their rights to participate in public affairs as well as free, prior and informed consent are restricted.[280] The disposal and recycling of batteries and e-waste can also impact the rights of workers who disassemble toxic electronics in informal sectors without protection.[281] Exposure to toxic materials can cause lung cancer and damage vital organs, while also increasing the risk of stillbirths, and contributing to neurological disorders.[282]

Additionally, e-waste processing currently heavily relies on child labour.[283] As innovation in solar energy largely relies on different chemicals and nanoparticles, there is a risk that concerns about harms to worker's health and the environment will intensify. Similarly, the scaling up of contract manufacturing poses risks for workers' rights.[284]

Despite the associated risks, in Asian-Pacific countries EV batteries are mostly recycled domestically by informal waste recyclers given their simplicity. But lithium-ion batteries are more complex to recycle. In the absence of domestic recycling capacity, trade in used batteries, which are internationally regarded as hazardous waste, comes in. Countries in the Asia-Pacific region often bear the environmental and human health costs of recycling operations, without benefitting from equivalent technological or economic benefits. This imbalance is further exacerbated by the fact that many used batteries are exported under ambiguous classifications, bypassing international environmental safeguards such as those outlined in the Basel Convention.[285]

The recycling rates for critical minerals vary considerably. However, overall, these rates are much lower than what the high demand for these materials would justify, often due to the challenges posed by underdeveloped recycling technologies, leading to the discarding of

[277] Submission by Greenpeace Southeast Asia.
[278] Submissions by SIRGE and Both ENDS and others.
[279] Submission by CarbonCare InnoLab.
[280] Submission by CarbonCare InnoLab
[281] Submission by Dharmesh Shah.
[282] Submission by Global Alliance on Incinerator Alternatives (Asia- Pacific).
[283] Sovacool et al. (n 249) 13-14.
[284] Mulvaney, "Opening the Black Box of Solar Energy Technologies: Exploring Tensions Between Innovation and Environmental Justice", *Science as Culture*, Vol. 22, No. 2 (2013) 231.
[285] Submission by Global Alliance on Incinerator Alternatives (Asia- Pacific).

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valuable resources.[286] Even for materials for which the overall recycling rates are relatively high, such as nickel and zinc, recycled materials cannot meet the high demand.[287]

The full life-cycle of critical materials produces a significant proportion of global greenhouse gas emissions.[288] Sand mining especially is not environmentally sustainable and contributes substantially to emissions.[289] If managed responsibly, however, the mining of critical minerals can be contained and carried out sustainably.[290]

In that context, advanced recycling technologies, such as those pioneered in Japan, which recover over 90% of materials from solar panels, must be shared with countries and cities that lack the capacity to develop such solutions. International technology transfer can make recycling a viable option for developing countries by reducing the costs of recycling, and increase the economic value of recovered materials.[291]

Current regulatory frameworks are lagging due to the pace of renewable energy deployment, which leaves a significant gap in ensuring responsible decommissioning practices. To mitigate these risks, developers must adopt responsible decommissioning plans aligned with international best practices, such as the Basel Convention on hazardous waste management.[292]

The European Union's Extended Producer Responsibility policies have mandated manufacturers to internalise recycling costs. These policies ensure that producers are accountable for the environmental and social impacts of their products throughout their life cycles.[293] However, due to the limited reach of EU regulations on waste and the ease of bypassing environmental regulation outside the EU where enforcement is often weak, there are gaps in the traceability of waste and in the fees necessary to cover collection and treatment.[294] The regulation does not yet offer sufficient incentives to consume less natural resources and prolong product life cycles.[295]

Establishing recycling fees at the point of purchase, as practiced in some EU countries, can fund future waste management efforts and reduce the financial burden on taxpayers and local

[286] See, for example, Graedel et al, "Recycling Rates of Metals – A Status Report" *UNEP, International Resource Panel* (2011), 9–22; Karali and Shah, "Bolstering supplies of critical raw materials for low-carbon technologies through circular economy strategies", *Energy Research & Social Science*, Vol. 88 (2022),1; Hagelüken and Goldmann, "Recycling and circular economy—towards a closed loop for metals in emerging clean technologies", *Mineral Economics*, Vol. 35 (2022) 540.
[287] European Commission, Report on Critical Raw Materials in the Circular Economy (2018), 24.
[288] See for example, Nelen et al., Improving the climate impact of raw material sourcing*, EEA Report No 08/2021* (2021), 7.
[289] Submission by Alliance for Responsible Mining Regulation.
[290] Bruckner, "Improving environmental and social practices in the mining sector is essential in the transition to renewable energy", *Journal of Energy & Natural Resources Law*, Vol. 41, No. 3 (2022), 2.
[291] Submission by CarbonCare InnoLab.
[292] Submission by Future Group.
[293] Submission by CarbonCare InnoLab.
[294] Berg et al (n 247).
[295] Bruyninckx et al. (n 290), 130.

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communities. Economic barriers, such as the high cost of recycling panels compared to landfill disposal, discourage businesses from adopting sustainable practices.[296]

Free trade agreements (FTAs) include specific critical raw material provisions which have the sole objective of reducing supply risk of raw materials by preventing export restrictions and export taxes. While recent FTAs tend to increasingly include environmental and human rights provisions, these are usually non-binding with few enforceable standards. [297] Except for under the EU–New Zealand FTA, disputes under these provisions are handled through dialogue mechanisms without the possibility of sanctions, hindering effective enforcement.[298] On the other hand, Investor-State Dispute Settlement (ISDS) provisions allow corporations to override Indigenous land claims and environmental protections.[299]

There is a broader trend that environmental costs of extraction are not internalized in prices. An internalization of environmental and social costs can help to transition towards a more sustainable economy. [300] Phase-out policies, market interventions and regulations that implement the 'polluter pays' principle can help phase-out resource-intensive and polluting practices. Such changes should be accompanied by supporting measures.[301]

[296] Submission by CarbonCare InnoLab.
[297] Submission by ClientEarth.
[298] Submission by SOMO.
[299] Submissions by Asia Pacific-Transition Mineral Accountability Working Group and SIRGE.
[300] Bruyninckx et al. (n 290), 119.
[301] Swilling et al., Tackling governance and financing for sustainability transitions, *International Resources Panel* (2025), 77.