The Clean Energy Paradox

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Picture the clean-energy future that most governments and corporations have been promising. Sunlight lands on solar panels covering rooftops and desert hillsides. Offshore wind turbines spin over grey seas. Electric vehicles move silently through city streets. The atmosphere slowly stops receiving the carbon dioxide that coal, oil, and gas have been adding for two hundred years. The appeal of this future is powerful, and the scientific case for pursuing it is overwhelming: the climate crisis is real, fossil fuels are the primary driver, and decarbonising energy systems is among the most important things humanity can do this century.

But there is a question embedded in the clean-energy vision that receives far less attention than the promise of emissions reductions. Solar panels are built from silicon, silver, aluminium, and copper. Wind turbines require steel, concrete, fibreglass, rare earth elements, and copper. Electric vehicles run on batteries containing lithium, cobalt, nickel, graphite, and manganese. Transmission networks and charging infrastructure demand vast quantities of copper and aluminium. The machines that will replace fossil fuels are not made of sunlight and wind. They are made of the earth. So it is worth asking: if the clean-energy transition requires enormous quantities of minerals, materials, and industrial manufacturing, what exactly do we mean when we call it clean?

The Myth: The transition to clean energy will reduce our dependence on natural resources and make energy production environmentally sustainable.

The Reality: Clean energy is not resource-free. Solar panels, wind turbines, batteries, and transmission infrastructure require significant quantities of minerals, land, water, and industrial capacity. The energy transition does not eliminate environmental pressures so much as change their sources, forms, locations, and scales. The real challenge is determining whether these new pressures can be managed within ecological limits while delivering the emissions reductions necessary to address climate change.

The Case for the Transition

Before investigating the paradox, the strongest case for clean energy needs to be stated plainly, because the environmental limitations of renewables are sometimes used to suggest a false equivalence with fossil fuels that the evidence does not support.

Lifecycle greenhouse gas emissions tell the clearest part of the story. A lifecycle assessment measures all emissions associated with an energy technology from raw material extraction through manufacturing, installation, operation, and decommissioning. For coal, these lifecycle emissions average around 820 grams of CO_2 equivalent per kilowatt-hour. For natural gas, the figure is approximately 490 grams, though methane leakage rates can push this considerably higher. By contrast, solar photovoltaic systems produce between 5 and 12 grams over their lifetimes, onshore wind between 7 and 11 grams, and nuclear power between 4 and 12 grams, according to harmonised estimates from NREL and the comprehensive review published in Nature Energy. These are not marginal differences. They are reductions of between 97 and 99% in climate impact per unit of energy delivered.

The benefits extend beyond carbon. Fossil fuel combustion is the leading source of ambient air pollution globally, responsible for millions of premature deaths annually from particulate matter, nitrogen oxides, and ozone exposure. Renewable energy systems produce no operational air pollution. Fossil fuel extraction contaminates water supplies through spills, leaks, and the disposal of produced water. The land disturbance created by fossil fuel infrastructure, from coal mines to oil sands operations to fracking pads, is extensive and often irreversible on human timescales. The methane leaking from oil and gas infrastructure represents a potent near-term climate forcing that is only partially captured in lifecycle emission estimates.

The starting point for any honest evaluation of the clean-energy transition must be that the system it is replacing has an environmental record that is, by any reasonable measure, substantially worse. The question this article investigates is not whether renewables are better than fossil fuels. They are, unambiguously, by the metrics that matter most. The question is whether they are as clean as they appear when only operational performance is considered, and whether the new environmental pressures they introduce can be managed within planetary limits.

The Material Reality

The energy transition is, at its physical foundation, one of the most material-intensive industrial projects in human history. Every solar panel, wind turbine, battery cell, and metre of transmission cable represents a demand on the earth that did not exist before.

The International Energy Agency's Global Critical Minerals Outlook 2025 documents the scale of what is required. Lithium demand rose by nearly 30% in 2024 alone, driven overwhelmingly by battery production for electric vehicles and grid storage. Demand for nickel, cobalt, graphite, and rare earth elements rose by 6 to 8% in the same year. For battery metals collectively, the energy sector accounted for 85% of total demand growth between 2022 and 2024. Looking further ahead, the IEA's Net Zero Emissions scenario projects lithium demand growing fivefold to eightfold by 2040, graphite demand nearly quadrupling, and nickel, cobalt, and rare earth element demand roughly doubling. Copper, which underpins virtually every electricity-related technology from grid lines to EV motors, is projected to face a supply gap: anticipated mine supply by 2035 is expected to cover only 70% of projected demand.

Different clean technologies have different material profiles, and treating them as interchangeable misrepresents the challenge. Solar photovoltaics require relatively large quantities of silicon, silver, and aluminium, but their rare mineral intensity has fallen dramatically over the past decade as technology improved. Silver use per panel has dropped by over 80% since 2010, and silicon consumption has fallen similarly. Onshore wind turbines are primarily steel and concrete, which are abundant and recyclable, though permanent magnets in their generators require rare earth elements, particularly neodymium and dysprosium, of which China controls over 85% of refined supply. Offshore wind uses more of everything: more steel, more copper, more rare earths, and more concrete per unit of energy output than its onshore equivalent, in exchange for higher and more consistent wind resources.

Batteries, whether in electric vehicles or grid-scale storage, present the most concentrated mineral challenge. A typical lithium-ion battery cell contains lithium, cobalt, nickel, manganese, and graphite in proportions that vary by chemistry. Lithium iron phosphate batteries, which are rapidly gaining market share, eliminate cobalt and nickel, substantially reducing both cost and ethical supply-chain risk. But they still require lithium and graphite. The question is not whether individual battery chemistries can be improved, but whether the aggregate mineral demand of a fully electrified transport and energy system can be supplied without creating environmental impacts that undermine the transition's sustainability case.

The Cost Beneath the Transition: Mining

Every tonne of lithium, copper, cobalt, and rare earth element extracted for the energy transition has to come from somewhere. That somewhere is, invariably, a place where land must be disturbed, rock must be moved, water must be used, and local ecosystems must absorb the consequences.

Lithium extraction from brine deposits in the Atacama Desert of Chile and the Salar de Olaroz in Argentina offers one of the most vivid illustrations of the tension between the global climate benefit of batteries and the local environmental cost of producing them. Evaporation-pond brine extraction, the dominant method, pumps mineral-rich water to the surface and concentrates it under the sun over months, consuming between 500,000 and 2 million litres of water per tonne of lithium carbonate produced. In a region where rainfall barely exists and water is already a contested resource, the impact on aquifer levels and on the flamingo populations and indigenous communities dependent on the salt flat ecosystems is a matter of documented concern. A 2023 study by the University of Chile found the Salar de Atacama's water table declining by 1 to 2 centimetres annually. A 2024 paper in Resources, Conservation and Recycling found that brine-based lithium production in the Atacama has among the lowest carbon footprints of any lithium source globally, precisely because of the abundant solar evaporation. The environmental tension is therefore not a simple one: lower carbon intensity at the production level does not mean lower ecological impact at the local level.

Cobalt mining presents a different set of concerns. The Democratic Republic of the Congo supplies approximately 70% of the world's cobalt, a significant portion of which comes from artisanal and small-scale mining operations associated with documented child labour, unsafe working conditions, and localised soil and water contamination. The geography of cobalt supply is concentrated in a single country with severe governance challenges, creating both an ethical and a supply-security problem for the clean energy transition. The battery industry has responded with accelerating development of cobalt-free or cobalt-reduced chemistries, but eliminating cobalt entirely from the supply chain while maintaining the performance characteristics required for aviation, long-range vehicles, and grid storage remains a work in progress.

Nickel mining in Indonesia, which has rapidly expanded to serve battery demand, provides another instructive case. Indonesia has become the world's largest nickel producer, with significant reserves in Papua and Sulawesi. The rapid growth of nickel smelting, often using relatively carbon-intensive processes, has raised concerns about the lifecycle emissions of the nickel going into electric vehicle batteries, and about the deforestation and coastal habitat loss associated with mining expansion in ecologically sensitive tropical regions. A 2023 analysis found that some Indonesian nickel processed through high-pressure acid leaching had lifecycle emissions comparable to, or higher than, some forms of fossil-fuel-derived energy when used in batteries, depending on the energy source powering the smelter. This finding illustrates that the environmental performance of clean-energy technologies cannot be assessed in isolation from the supply chains that produce them.

It would be misleading, however, to present mining impacts as either unique to the clean energy transition or as fixed and irremediable. The fossil fuel system also requires extensive mining: coal extraction, oil sands operation, and natural gas fracking each carry their own substantial landscape, water, and community impacts. The difference is one of type rather than of presence or absence. Fossil fuel extraction is ongoing and cumulative: the system requires continuous consumption of fuel throughout its operation. Mining for renewable energy infrastructure is primarily upfront: once a wind turbine is built, it does not require further iron ore extraction for the next twenty-five years. This distinction, which we will examine more closely, is one of the most important in understanding whether the transition genuinely reduces or merely shifts humanity's dependence on extractive industry.

The Water Dilemma

Water and energy are deeply interconnected, and the energy transition reshapes their relationship in ways that are rarely fully acknowledged.

Thermal power generation, whether coal, gas, or nuclear, uses water extensively for cooling. A coal-fired power plant typically withdraws 1,000 to 2,000 litres of water per megawatt-hour of electricity generated, and consumes (evaporates) 0.6 to 1.5 litres per kilowatt-hour. Nuclear plants use similar quantities. In aggregate, power generation is one of the largest water users in many water-stressed economies. Shifting electricity production to solar and wind reduces operational water consumption dramatically: photovoltaic solar panels and wind turbines require virtually no water during operation.

But the replacement of one water pressure with another requires attention. Lithium extraction, as described above, is water-intensive in regions of severe water scarcity. Copper mining in Chile and Peru, which sit at the intersection of one of the world's driest deserts and some of its highest-altitude glaciers, uses water that increasingly competes with local communities, agriculture, and fragile high-altitude ecosystems. The hydrogen economy, which many net-zero scenarios rely on for hard-to-electrify sectors, requires approximately 9 litres of water per kilogram of hydrogen produced by electrolysis. At the scale envisaged, this creates a further water demand that needs to be located thoughtfully relative to water availability.

The critical analytical point is that global water consumption statistics can be misleading. A tonne of water consumed by a wind turbine manufacturer in Norway has different ecological significance from the same quantity consumed by a lithium brine operation in the Atacama or a copper mine in the Peruvian highlands. The environmental impact of water use cannot be evaluated outside of its regional hydrology. This matters for policy: a sustainable energy transition requires attention not only to how much water the system uses globally but to where that water is consumed and what the local capacity to sustain that consumption is.

Land, Biodiversity, and the Spatial Problem

Renewable energy systems require land. Wind and solar farms occupy space in ways that fossil fuel plants, with their high energy density, largely do not. This is one of the most frequently cited objections to large-scale renewable deployment, and it deserves careful analysis rather than dismissal.

Solar photovoltaic systems have a power density of roughly 5 to 20 watts per square metre, depending on latitude and panel efficiency. Coal and gas plants operate at power densities of 500 to 1,000 watts per square metre, excluding the land used for fuel extraction. This difference in energy density means that solar and wind require considerably more land per unit of power generated at the point of installation. However, the comparison becomes more nuanced when the full footprint of fossil fuel systems is considered. Coal mining, oil sands extraction, natural gas fracking, fuel transportation corridors, pipeline rights-of-way, and ash disposal sites collectively occupy substantial land areas, much of which is rendered ecologically impaired on long timescales. A 2022 NREL study found that meeting 80 to 100% of US electricity needs from renewables by 2035 would require less than 1% of the lower 48 states, an area comparable to or smaller than the existing footprint of the fossil fuel industry.

Wind farms present an interesting intermediate case. The spacing between turbines, typically around one turbine per square kilometre, means wind farms have a large nominal footprint. But the land between turbines is typically compatible with agriculture, grazing, and wildlife movement. The actual physical disturbance, around the tower base and access roads, is a small fraction of the total area. Offshore wind eliminates land-use competition with ecosystems and agriculture entirely, at the cost of higher material requirements and more complex installation.

The genuine land-use concern for renewables is less about total area than about where that area is located. Large solar installations on desert land in ecologically low-sensitivity areas carry very different biodiversity implications from those sited on biodiverse grasslands or near migratory corridors. The rapid expansion of solar in parts of the Indian subcontinent, southeastern Europe, and the American West has in some cases proceeded with insufficient attention to local ecology. Agrivoltaics, which combine solar generation with agricultural use of the same land, and dual-use designs that incorporate pollinator habitat between panel rows, represent approaches that can reduce the land-use conflict significantly. The tension between decarbonisation and biodiversity conservation is real, but it is a tension that can be managed through careful siting, design, and policy, rather than an inherent contradiction.

A Shift in Extraction, Not an End to It

One of the most important conceptual distinctions in evaluating the clean energy transition is the difference between a continuous fuel economy and a materials economy.

Fossil fuel systems consume their resource input with every unit of energy produced. A coal-fired power plant burns coal continuously: the fuel is extracted, transported, combusted, and gone. The environmental impact of that system accumulates with every tonne of fuel burned. As long as the plant operates, the extraction continues. Renewable energy systems work differently. A wind turbine or solar panel requires its material inputs principally at the point of manufacture and installation. Once built, it generates energy for twenty to thirty years without any further fuel extraction. This distinction is significant: it means that the extractive burden of a renewable energy system is largely a one-time investment rather than a continuous withdrawal.

The IEA has quantified this distinction in its lifecycle resource comparisons. Over a forty-year operational period, a coal power plant requires approximately seventeen times more materials per unit of energy delivered than a solar PV system, when fuel and infrastructure are both included. The solar system front-loads its material demand; the coal system distributes it continuously over decades. This structural difference suggests that the clean energy transition involves a genuine reduction in cumulative extraction over time, even though the upfront demand surge required to build the new system is substantial.

This does not, however, mean the transition is resource-neutral. The scale of infrastructure required to replace a global fossil fuel system operating at 500 to 600 exajoules annually is enormous. Recycling from end-of-life technologies can help: the IEA estimates that by 2040, recycled copper, lithium, nickel, and cobalt from clean energy applications could reduce primary supply requirements by 10 to 30%. But the gap between what recycling can supply and what demand will require means that primary mining will remain significant throughout the transition period. The question is not whether extraction continues, but whether it can be conducted at a scale and in a manner consistent with ecological limits and community rights.

Visualising the Clean Energy Paradox

The chart below places two critical dimensions of the clean energy paradox side by side: lifecycle greenhouse gas emissions per kilowatt-hour on the left, and relative material intensity on the right, using coal as the baseline.

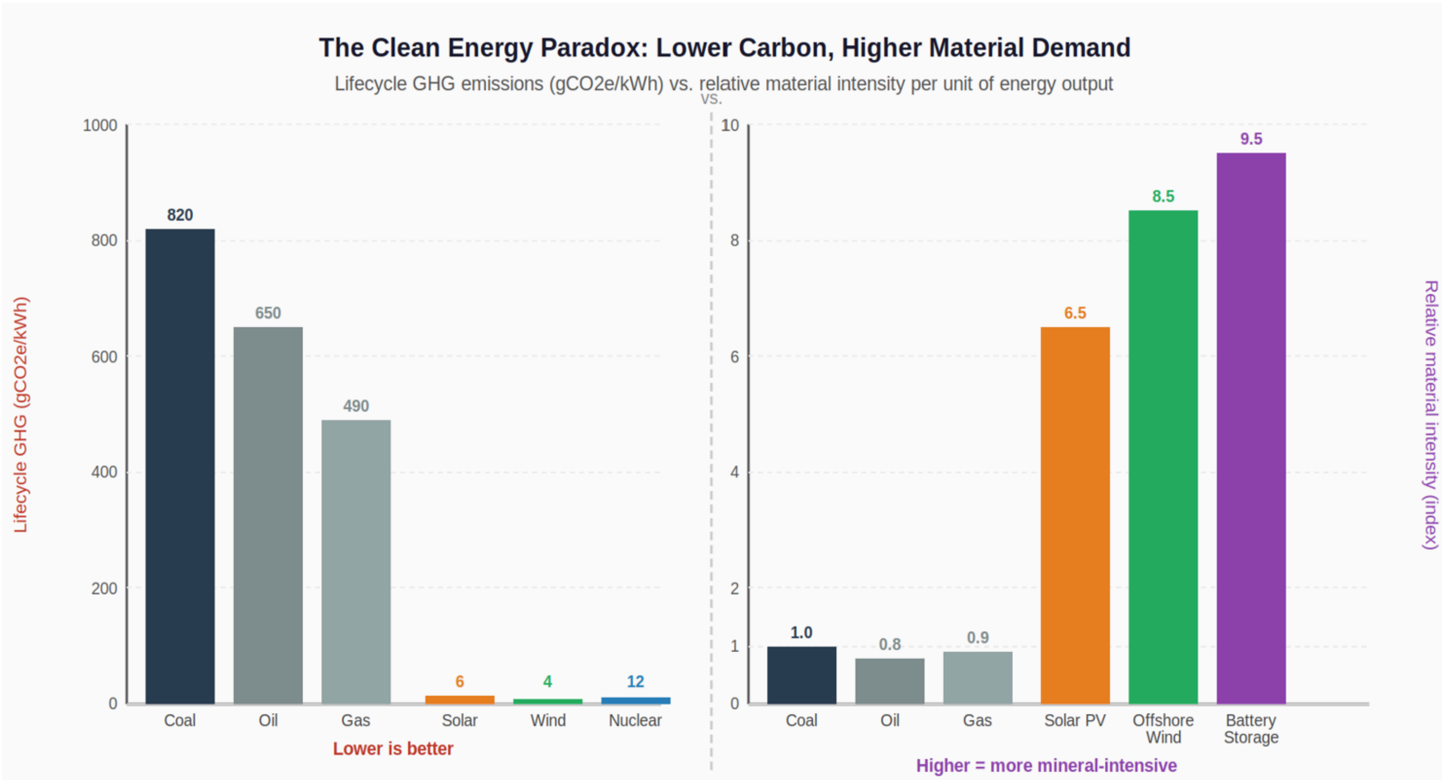

Figure 1: The Clean Energy Paradox visualised. Left panel shows median lifecycle greenhouse gas emissions per kWh across energy technologies, illustrating the 97-99% carbon advantage of solar, wind, and nuclear over fossil fuels. The right panel shows relative material intensity per unit of energy output over the technology's lifetime, indexed to coal (=1.0), illustrating that low-carbon technologies require substantially more minerals and materials per unit of energy than their fossil-fuel equivalents. Material intensity values are illustrative indices derived from IEA Global Critical Minerals Outlook 2024 and 2025, IRENA Materials for the Energy Transition (2023), and peer-reviewed lifecycle assessment literature. GHG values are median lifecycle estimates from NREL LCA Harmonisation (2024) and Hertwich et al., Nature Energy (2015).

The pattern in the chart reveals that technologies that emit the least carbon over their lifetimes are, in general, the most material-intensive per unit of energy delivered. Coal sits in the top-left of the conceptual space: high carbon, low mineral demand beyond the steel and concrete of the plant itself. Battery storage sits in the bottom-right: very low operational carbon, very high mineral intensity. Solar PV and wind fall between these extremes on the material axis while remaining orders of magnitude lower on the carbon axis.

Does Technology Changes the Equation?

The mineral intensity of clean energy technologies today is not the mineral intensity they will have in ten or twenty years. Technological change has already transformed the picture substantially, and there are good reasons to expect it to continue doing so.

The most consequential recent shift in battery chemistry is the rapid rise of lithium iron phosphate, or LFP, batteries. LFP cells eliminate cobalt and nickel entirely, replacing them with iron and phosphate, which are abundant and broadly distributed geographically. The trade-off is lower energy density: LFP batteries are heavier for the same energy storage capacity, making them better suited to stationary grid storage and short-range vehicles than to long-range applications. By 2024, LFP had captured a majority of new battery installations in China and was expanding rapidly in global markets. The cobalt problem, which attracted enormous attention and concern five years ago, is becoming structurally less significant as battery chemistry diversifies.

Sodium-ion batteries represent a further potential shift, replacing lithium with sodium, which is effectively inexhaustible and geographically ubiquitous. Early sodium-ion systems are now entering commercial deployment, with lower energy density than lithium-ion but cost and supply-chain advantages that may make them appropriate for stationary storage applications. Solid-state batteries, still largely in development, promise higher energy density and potentially lower material requirements through more efficient use of active materials. Rare-earth-free permanent magnets are under active development for wind turbine generators and EV motors, targeting the neodymium and dysprosium dependency that currently concentrates supply risk in China.

For solar PV, material intensity has been falling consistently for a decade. Silver consumption per panel has dropped by more than 80% since 2010 as cell designs have become more efficient. Silicon wafer thickness has been halved. Perovskite solar cells, which promise higher efficiency and lower material requirements than silicon-based designs, are approaching commercial viability. Tandem perovskite-silicon cells have achieved laboratory efficiencies above 33%, compared to the 20 to 22% typical of commercial silicon panels today.

These technological developments are encouraging, but they must be read against a recurring theme of this blog series. Efficiency improvements at the unit level do not automatically translate into reduced total environmental pressure if the overall scale of deployment continues to grow. If improving battery efficiency enables cheaper storage, which enables more ambitious renewable targets, which drives more battery production, the absolute mineral demand may still rise even as the per-unit demand falls. The Jevons paradox, which has appeared in every previous Eco-Mythbusters investigation, operates here too.

The Scale Problem: Building a World on Clean Energy

The IEA's Net Zero by 2050 pathway requires global electricity generation to roughly triple from today's levels by mid-century, as transport, heating, industry, and data infrastructure all shift from fossil fuels to electricity. This is not a modest reengineering of the energy system. It is a fundamental reconstruction of the physical infrastructure of modern civilisation, conducted over approximately twenty-five years.

The scale of mineral demand that this implies is not simply proportional to today's clean-energy sector. A doubling of lithium demand, for instance, requires not only the same number of mines producing twice as much, but entirely new mine development, processing infrastructure, and supply chains in countries that may lack the regulatory frameworks, environmental safeguards, and infrastructure to manage rapid extraction growth responsibly. The IEA notes that graphite and rare earth element supplies, even under the most optimistic project pipeline assumptions, would cover only 35 to 40% of demand under N-1 supply disruption scenarios in 2035. For copper, the gap between anticipated supply and projected demand narrows to a potential shortfall by the same date.

Developing-country energy access adds a further dimension to the scale question. Sub-Saharan Africa, South and Southeast Asia, and parts of Latin America have legitimate claims to the energy consumption levels that support modern living standards. Meeting those claims through clean energy, rather than replicating the fossil-fuel path that industrialised economies followed, is both the right approach and a substantial additional demand on the global mineral supply system. The countries most likely to host future clean-energy mineral extraction are often those with the least capacity to enforce environmental and social safeguards in the mining sector. This is one of the most ethically complex dimensions of the energy transition, and one that receives insufficient attention in most discussions of the clean-energy future.

Is Clean Energy Actually Sustainable?

Having examined the evidence from lifecycle emissions to mineral demand, from water stress to land use, from mining impacts to technological trajectories, the honest answer to this section's question is: it depends, and on what we choose to do about things that are currently not being done adequately.

The arguments supporting the transition are strong and well-founded. Lifecycle greenhouse gas emissions from solar, wind, and nuclear power are between 97 and 99% lower than from coal and gas. Operational air pollution is eliminated. The transition from a continuous-fuel system to a materials-based infrastructure means that cumulative extraction over time can be lower even if upfront demand is high. Battery technology is diversifying toward less problematic chemistries. Material intensity per unit of renewable energy is falling. Recycling is beginning to supply a meaningful secondary stream of critical minerals, even if it cannot yet meet primary demand growth.

The arguments requiring serious caution are also well-founded. The Atacama and Indonesian cases show that real ecological harm is occurring now in the supply chains of clean energy, not in some hypothetical future. Copper supply faces structural gaps against projected demand. Geographic concentration of mineral supply in a small number of countries, several of which face governance challenges, creates supply-chain fragility. Land-use conflicts between renewable deployment and biodiversity are arising in ecosystems that cannot easily absorb them. The scale of energy demand growth, particularly in the developing world, may outpace efficiency improvements and recycling gains.

The most honest conclusion is that the energy transition represents a genuine, substantial improvement in the primary driver of environmental harm, which is climate change, while simultaneously creating new pressures that are neither trivial nor inevitable. They are manageable under the right conditions: responsible mining governance, transparent supply chains, investment in recycling infrastructure, careful siting of renewable installations, accelerated technological development toward less material-intensive systems, and, crucially, some reduction in the total demand growth that is continuously expanding the scale of the challenge.

A clean energy system that runs on minerals extracted without adequate environmental safeguards, in water-stressed regions, from ecosystems that cannot sustain the disturbance, is not sustainable in any meaningful sense of the word. But neither is continuing to run the world on fossil fuels while waiting for a perfect solution. The choice is not between a flawed clean-energy transition and a benign status quo. It is between a clean-energy transition conducted with or without the environmental discipline it requires.

Conclusion

The transition to clean energy will unambiguously reduce the greenhouse gas emissions that are destabilising the climate, eliminate the air pollution that shortens millions of lives annually, and remove the continuous extraction of fossil fuels that has reshaped the earth for two centuries. These are genuine, transformative improvements that no honest accounting of the energy transition can ignore.

But clean energy is not impact-free energy. It is energy whose environmental footprint has a different composition: less carbon, more minerals; less atmospheric damage, more localised mining and water impacts; less continuous fuel consumption, more upfront infrastructure investment. The philosophy of this blog series holds here as it has throughout: powerful ideas become misleading when reduced to slogans. Calling an energy system clean because it does not burn fossil fuels while ignoring what it extracts, where, at whose cost, and with what ecological consequences, is the same error as calling a building sustainable because it has solar panels while ignoring the materials that built it.

The energy transition is necessary. The scale and pace of decarbonisation required by the remaining carbon budget make it urgent. But making it genuinely sustainable requires asking harder questions than simply whether something is renewable. It requires asking what it is made of, where those materials come from, what happens to the land and water where they are extracted, how the end-of-life materials will be recovered, and whether the total system, from mine to panel to grid to recycling plant, operates within the limits that the natural world can sustain.

Clean energy may be the path away from fossil fuels. But whether it becomes a path toward sustainability depends on what we build, what we extract, how much we consume, and what happens to the materials when their useful lives end.

When the Clean Energy Transition is Genuinely Sustainable:

- When mining operations for critical minerals are conducted under rigorous environmental and social standards, with independently verified water management plans, community consultation, biodiversity impact assessments, and rehabilitation obligations that are actually enforced.
- When renewable energy infrastructure is sited with care for local ecology, using degraded or low-biodiversity land where possible, incorporating agrivoltaic and wildlife-compatible

designs, and subjecting sensitive-area proposals to genuine environmental review rather than permitting expedience.

- When battery chemistry innovation continues to reduce dependence on the most geographically concentrated and ecologically sensitive minerals, and when recycling infrastructure is built at sufficient scale to recover the materials embedded in first-generation clean-energy equipment before they reach end of life.
- When the total demand for energy is also addressed through efficiency, demand management, and changes in consumption patterns, so that the mineral and land requirements of the transition do not grow faster than the environmental improvements it delivers.

When It Isn't:

- When the environmental credentials of a renewable technology are assessed only on the basis of its operational emissions, ignoring the upstream extraction, manufacturing, and downstream waste management of the minerals and materials that make it possible.
- When the geographic concentration of critical mineral supply in a small number of countries with weak environmental governance is treated as a future supply-chain risk rather than a present ecological and human rights concern requiring immediate policy attention.
- When efficiency improvements in individual clean-energy technologies are cited as evidence that the overall environmental pressure of the transition is declining, without accounting for the expanding scale of deployment that may offset per-unit gains at the system level.
- When developing-country energy access is framed as a demand problem to be managed rather than a legitimate aspiration to be served, without acknowledging that the countries most likely to mine the minerals for the global energy transition have the greatest claim on the benefits of the energy system those minerals will build.
- When the clean-energy transition is treated as a completed achievement rather than an ongoing responsibility, as if reaching renewable targets on a grid eliminates the obligation to manage the full lifecycle of the infrastructure that delivers them.

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