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Winds of change: Supply chain analysis of a wind turbine

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Abstract
Skeptics of degrowth often place their hopes in clean energy technologies, such as wind turbines, to offset the consequences associated with a growing economy that demands equally high rates of energy. Rather than reduce economic production, as proponents of degrowth argue is necessary to mitigate social and environmental consequences, clean energy is held up as a perfect ‘business as usual’ solution that will allow economic growth to continue. Taking a degrowth perspective, this paper uses a supply chain analysis to de-fetishize the wind turbine as a source of immaterial clean energy. While affirming that renewable energy technologies such as wind turbines and solar panels are necessary, they are insufficient from a degrowth perspective to offset the consequences of continuous growth. Instead, technological improvements, including wind power, must be complimented by policy that reduces economic impact overall.

For many, wind turbines are the most visible symbols of clean, renewable energy. For others, wind turbines “are themselves embodiments of fossil fuels” (Smil, 2016, p.27). A single wind turbine is the culmination of enormous production processes that include the transportation of tons of steel and raw materials by truck, the preparation of sites by cranes and excavators, and the coordination of freight trains and cargo ships (Bai et al., 2023; Farina & Anctil, 2022; Li, Mogollón, Tukker, Dong, et al., 2022; Li, Mogollón, Tukker, & Steubing, 2022; Yang et al., 2018). Rotor masses alone would require ninety million metric tons of crude oil. A 5 megawatt turbine requires 150 metric tons of steel, 250 metric tons for rotor hubs and nacelles, and five hundred metric tons for towers. An aggregate of 2.5 terawatts would require 450 million metric tons of steel, and all these quantities exclude considerations for the towers, copper wires, and transformers required to connect and run it all (Smil, 2016).

Wind turbines are materially intensive technologies in terms of their manufacturing, transportation, installation, and upkeep. Further, they are networked commodities requiring infrastructure such as grids, cables, and generators. Yet, from a degrowth perspective, they are far more (Hickel, 2019c). Windmills are reliant on fossil fuels not only in their manufacture, transportation, and installation, but their generators, cables, and energy storage capacities are further embodiments of non-renewable metals and minerals, specifically, copper, lithium, dysprosium, and neodymium. This paper uses a supply chain analysis to critically materialize the wind turbine from a degrowth perspective using a Texas-based wind farm as a case study. To begin, I outline a theoretical degrowth framework and describe my methodology, followed by an overview of the wind turbine supply chain within the US context, using the Roscoe Wind Farm as a more particular case study. I conclude by analyzing the challenges of the renewable energy market from a degrowth perspective. Ultimately, analyzing the wind turbine as a commodity implicated in numerous overlapping supply chains suggests that renewables, such as wind, are necessary but insufficient for mitigating ecological crises without concurrent overall reductions in the scale of global production and consumption—i.e., *degrowth*.

1. Degrowth

Degrowth is a critique of economic growth, where critique means both criticism and elucidation. Paul Aries describes degrowth as a ‘missile word’ whose purpose is to explode and/or disrupt hegemonic discourses rather than offer programmatic solutions (Aries, 2005; cited in Latouche, 2009, p. 7). However, degrowth consists of an additional positive discourse promoting growth-agnostic, socio-economic systems that foster genuine human flourishing, autonomy, and democracy. These two sides of degrowth, the critique of growth and the “concrete utopias” of post-growth society, are joined by a spectrum of studies, models, experiments, policy proposals and theories that have made degrowth an eclectic and inter-disciplinary field (Engler et al., 2024; Fitzpatrick et al., 2022; Kallis et al., 2018, p. 308).

Given the fundamental constraints of the bio/geo-sphere, proponents of degrowth argue that global, state, and even municipal economies should not presuppose, or plan for, infinite growth. Since the ground-breaking work of Nicholas Georgescu-Roegen (1971, 1976, 2011), ecological economists have argued that the classic theories of traditional economics are misleading in an entropic universe because such theories tend to presuppose an infinitely expanding system (the economy) that nevertheless depends upon a finite base (the bio/geo-sphere). Attempts to reconcile the two are referred to as green (or sustainable) growth (Hickel & Kallis, 2020; Jackson, 2009; Parrique et al., 2019). A "steady-state" system, on the other hand, is one in which the scale of material throughput or emissions in an economy does not meaningfully increase (Daly, 1991, 2014). Proponents of degrowth propose that a steady state is desirable but would only be possible following intentional economic contraction (Schmelzer et al., 2022).

Those writing and researching degrowth place increasing emphasis on geographic differentiation regarding necessary pathways to low/no-growth scenarios. Researchers, such as Jason Hickel, argue that the Global South, which has disproportionately suffered the consequences of the Global North's extraction and pollution (itself constituting a form of neocolonialism), should carry a much lower responsibility to reduce material throughput and emissions than the Global North (Fanning et al., 2021; Hickel, 2019b, 2019a, 2020, 2021b, 2021a; Hickel & Slamersak, 2022). There are many states that still require crucial infrastructure and that have been held back by colonial and neo-colonial regimes and exploitation (Hickel, 2018). Therefore, Hickel and others argue the Global North ought to consume and extract less to make resources available for the South while gradually decreasing overall ecological impact.

Renewables occupy a complex position within the degrowth landscape. On the one hand, they are clearly tools that are useful for reducing carbon emissions. Degrowth researchers are skeptical about this though given the propensity for efficiency gains to ultimately translate into increasing consumption and production (this is known as the Jevon's paradox; Alcott, 2005; York & McGee, 2016). Renewables are closely related to the idea of 'decoupling,' a concept that is frequently discussed in the degrowth literature. Decoupling refers to a simultaneous increase in economic output (GDP) and decrease in environmental impact. However, there is a significant difference between relative decoupling, where there is a reduction in the material/emission intensity relative to economic output, and absolute decoupling where material/emission intensity declines "in absolute terms, even as economic output continues to rise" (Jackson, 2009, p. 84). There is also "sufficient absolute decoupling" whereby environmental impact is kept below planetary boundaries as GDP continues to grow (Parrique et al., 2019). Researchers further differentiate between territorial and regional scales, emissions, eco-/water-footprint, etc. in determining the potential for decoupling (Parrique et al., 2019). Overall, though *relative* decoupling is possible, there is no evidence that *absolute* decoupling is possible, or that it will be in the near future (Hickel, 2021a; Hickel & Hallegatte, 2022; Hickel & Kallis, 2020; Jackson, 2009; Mastini et al., 2021; Raworth, 2017; Vogel & Hickel, 2023; Wiedenhofer et al., 2020; Xue, 2012).

Moreover, no absolute decoupling (sufficient or otherwise) has been observed regarding the scale of materials used in the global economy (i.e., the material footprint), which is of particular consequence for the production of renewable energy (Schandl et al., 2018; T. O. Wiedmann et al., 2015). Renewables are related to decoupling insofar as they are imagined, by proponents of regular, green, or clean growth, to be a 'silver-bullet' that will eliminate the emissions and material intensity of 21st century economies (the digital frontier is proposed to play a similarly important role) (Meyers, 2024; Raworth, 2017, p. 258; Santarius et al., 2020). The degrowth literature is clear: there are no silver bullets. Renewables are, at best, an energy buffer for transitioning to a less impactful economy, and at worst, an illusion that permits the continued degradation of earth's ecosystems. That does not mean that there will not be significant material trade-offs in a successful large-scale transition to renewables. For example, the footprint of rare earth metals in particular will increase as the footprint for coal likely decreases (Krane & Idel, 2021; Nijnens et al., 2023; Watari et al., 2021). From a degrowth perspective, the more significant point is that despite these trade-offs, renewable energy still has a material footprint whose specific make-up differs from non-renewables in important and potentially consequential ways. Rather than pursue absolute decoupling, a degrowth perspective argues that decreasing the rate of economic growth in concert with increasing global renewable energy capacities is necessary.

Decoupling has often been misattributed to state economies that have effectively outsourced their emissions to other states (Mauerhofer, 2013; Parrique et al., 2019; T. O. Wiedmann et al., 2015). For example, in the UK, claims regarding the decoupling of economic growth from environmental impact relied on importing high-emission goods from other states (Syed, 2019). However, outsourcing the burden of producing high-emitting goods is only one way that affluent states (often in the Global North) exploit other states (often in the Global South). Concerning renewables, a degrowth analysis must be sensitive to global asymmetries that produce neocolonial forms of extraction wherein resources are extracted from dependent states and consumed by affluent states in the name of a ‘green transition.’ Wind turbines, and other renewables, are at the forefront of these new commodity frontiers (D’Alisa et al., 2015; Moore, 2000) and the extent to which they become purely exploitative of or beneficial to the Global South is contingent on how these frontiers are regulated (Beckert et al., 2021; Neimark et al., 2016).

2. Methodology

I materialize and de-fetishize the renewable energy of a windmill using a supply chain analysis, referring to one of the largest wind farms in the US for context. Of the three types of turbines installed at the farm (produced by Mitsubishi, General Electric, and Siemens), I focus on the Siemens 2.3 MW turbines. Siemens is one of the three largest competitors in the renewable wind energy industry—the other two are General Electric and Vestas (Freedonia, 2020a, 2020b). Ideally, the analysis would track the supply chain of the Siemens 2.3 MW turbine from subcomponent extraction to decommission. However, this was not possible given the availability of data. Instead, I conducted a literature review of supply chain analyses for renewable energy in general and for wind turbines (onshore and offshore) in particular. US market-based reports on Siemens and the wind turbine market proved invaluable, as did the US government’s own supply chain analyses for wind turbines and valuable minerals. Lastly, several news reports drawn from the IBISWorld database were consulted for information on the development and reception of the Roscoe Wind Farm.

3. Wind turbines

Harnessing wind power has a long history. The principles of harnessing energy from the wind have remained roughly the same throughout history: blades or sails are turned by the wind and connected to an axel which, when spun, creates energy that can be used for other tasks such as milling flour, pumping water, and grinding corn (Lawton, 2021). Contemporary wind turbines build on this model in several ways. Wind turbines can rotate on a vertical or horizontal axis, but most windfarms install horizontal turbines (DOE, 2022). There are five main components of a wind turbine: the nacelle, the tower, the grid interconnection equipment, the foundation, and the blades. Most wind turbines consist of three blades that are engineered to efficiently capture the most wind possible. Directly behind the blades sits the nacelle, a large 'box' that houses the generator, gearbox, yaw systems, and electronics. The nacelle sits atop the turbines' tower, which is typically made of steel, though some are concrete or hybrids of concrete and steel (DOE, 2022). The tower sits on a concrete slab that serves as the foundation and is sometimes reinforced by steel and iron. Lastly, the energy generated through the rotors to the nacelle is passed to substations through copper wires (DOE, 2022). Beyond these five parts of the wind turbine, other critical subcomponents include the generators, gearboxes, bearings, large castings, forged rings and shafts, and semiconductors (DOE, 2022). Power is generated through the wind turbine via its rotating blades which translate the wind power through a generator inside the nacelle. The generator amplifies the wind energy harnessed by the blades, which in turn are engineered to maximize efficient capture of local wind conditions (Ristoff, 2021; World Bank Group, 2017). Most wind turbines also feature sensors that tell the head to pivot to where the wind is blowing strongest. Finally, power passes through connection cables to a power grid for use or storage.

Wind turbines used in the renewable energy sector are either onshore or offshore turbines. Though the main parts involved are similar (blades, nacelle, foundation, grid connections, and tower), there is a significant difference in generators (DOE, 2022; IEA, 2022; World Bank Group, 2017). Technically, there are four types of generators but these can be simplified into two classes: gear-box generators and permanent magnet generators (IEA, 2022). The difference between these generators is significant from a degrowth perspective as while gearbox generators are less reliable (requiring more general maintenance and repair) and more cumbersome, they are somewhat preferable, from a materials standpoint, to the permanent magnet generators which use the rare earth elements neodymium and dysprosium (DOE, 2022). Gear box generators are common in onshore wind turbines, whereas permanent magnets are more common in offshore turbines where they are less accessible since permanent magnet generators require less maintenance and upkeep.

Horizontal turbines, the industry standard on wind farms, require large spaces suitable for the turbines' immense blades (DOE, 2022). Wind turbines serve utility-scale and distributed power applications. In the US, wind farms that are best suited for utility-scale application are categorized as independent producer, investor-owned, public, and cooperative. Independent producers sell their own wind energy wholesale or to other utilities markets. Investor-owned wind farms provide generation, transmission, and distribution of their own electricity. Public utilities work with the government to supply reliable electricity to the public. Lastly, cooperatives produce and distribute wind energy for each other and are subdivided into rural electric coops and community-owned projects (Ristoff, 2021, p. 10).

RWF is an investor-owned farm that pays royalties to the landowners from whom the land is rented. The farm is located forty-five miles south-west of Abilene, Texas. It is one of the biggest in the world and was completed in four phases with a capacity of 781.5 MW (Anonymous, 2009; Nadeem, 2008). The site is mostly leased from cotton farmers, who are able to continue using the land to farm while the turbines operate (LeBlanc, 2015); the project otherwise provides upwards of sixty-seven jobs. Construction began on the project in May 2007, and it became operational in 2009. The farm has 627 turbines (Gonzalez, 2009)—55 siemens 2.3 MW turbines, 406 Mitsubishi 1 MW turbines, and 166 GE 1.5 MW turbines (Power Technology, 2020). The turbines range between 350ft and 415 ft tall and stand 900 ft apart. The energy generated by the farm is supplied to TXU Corporations subsidiary TXU wholesale and CPS energy (Anonymous, 2008; Global Power Report, 2007; Natural Gas Week, 2007).

The state of Texas generates the most wind power of any US state. According to a recent report, "if Texas were a country, it would rank sixth in the world for total wind capacity" (Ristoff, 2021, p. 19). The southwest region produces 36.3% of the nation's entire wind capacity due to its exposure to strong power-producing winds, and 26.9% of the capacity in the region is produced by Texas.

Of the three manufacturers who supplied turbines to RWF, Siemens and General Electric both have a significant stake in the United States wind turbine industry (Freedonia, 2020a; Petridis, 2022; Ristoff, 2021). The Siemens 2.3 MW turbine was produced by the Denmark manufacturer Siemens Wind Power A/S which has since been taken over by Siemens Gamesa Renewable Energy (based in Spain) since 2017 (Freedonia, 2020a). The turbine has three blades and is fitted with a planetary gearbox manufactured by Winergy, an international manufacturing company specializing in generators and a subdivision of Flender, with nine plants across Europe, Turkey, and Australia. The 2.3 MW turbine’s 262 ft tower is made from steel and painted for protection from corrosion (Siemens, 2011).

4. Supply chain

Before wind turbines are operational, they must be manufactured, transported, installed, and connected to grids for distribution, all of which are high-emission processes. Together, the rotors and nacelles for the Siemens 2.3 MW turbine weigh 142 tons (60 and 82 respectively) and would likely have been shipped from Denmark to the Houston port, before being transported to Roscoe on a flatbed, and finally lifted onto the tower using a crane (Siemens, 2011). In a study of 66 projects installed by an unnamed company across four countries (Germany, China, Russia, and Turkey), Lundie et al. (2019) confirmed several ‘hotspots’ where significantly high energy, water, and carbon footprints were associated with the 66 wind projects. Confirming the work of other researchers, Lundie et al. found that “supply chain impacts often account for the majority of environmental and societal effects” (Ibid, p. 1042). Their study also confirmed a recent review showing that “10-70% of environmental impacts and resource use are embodied in global trade, i.e., occur along international supply chains” (Ibid, p. 1043; referring to Wiedmann & Lenzen, 2018). According to the study (p. 1048):

> *the greatest share of energy was consumed by the following industries: Electricity (26%), Mining and Quarrying (18%), Petroleum, Chemical and Non-Metallic Mineral Products (17%, which includes concrete) and Transport (17%). The majority of the carbon footprint is exerted by almost the same industries, with an even greater share from the Electricity sector of 33%. Hotspots of the water footprint were found in the sectors Other Manufacturing (22%), Metal Products (20%), Petroleum, Chemical and Non-Metallic Mineral Products (18%) and Electrical and Machinery (15%).*

Lundie et al. also make it clear that impact is largest in several tiers removed from the actual site of installation. The main impacts are thus attributable to supplier tiers. The authors argue that companies must calculate and account for *entire* supply chains in estimating long-term sustainability.

The supply chains of renewable energy is typically studied in five phases: procurement, generation, transmission, distribution, and demand; or three processes: upstream, production, and downstream (Jelti et al., 2021). Both approaches split the renewable energy supply chain into the initial capturing of power (in this case wind), the translation of that power into different forms of energy (electricity), and the distribution or marketing of the produced energy. Downstream processes (transmission, distribution, and demand) are complex due to the inherent intermittency of renewable energy. Currently, there is controversy over what energy is prioritized on energy grids when capacity exceeds demand (UCS, 2021). This is complicated (though not irremediably) by the fact that renewables such as wind and solar are infrequent, fluctuating sources of energy. Sometimes the sun shines and the wind blows, but sometimes it does not, and rarely does it do either consistently. This means that storing excessive energy for use during low-supply periods (cloudy or still days) is necessary for pragmatic renewable-energy grid-integration. Historically, the solution to storing excess wind power has been converting it into hydraulic power, wherein water is pumped to a high elevation using the excessive energy where it is stored until needed (IEA, 2022; World Bank Group, 2017). However, not only does this solution require a large body of water on standby, it also requires elevation. An alternative is battery storage, which requires lithium. This is the solution currently being implemented at Roscoe (Anonymous, 2018; Newswire, 2017).

There are generally four phases to the wind turbine lifecycle: development, installation, operations, and de-commissioning (Poulsen & Lema, 2017). Development involves planning and locating sites for potential wind farms. The installation phase includes an inbound supply chain (the manufacturing of nacelles, blades, tower, foundation, cables, and substations) and an outbound supply chain (farm infrastructure such as sub-stations, storage sites, warehouses, etc.). The operations and maintenance supply chain runs for the entire duration of the turbine's lifespan and refers to the supplies and resources required to keep the turbine operating. Finally, de-commissioning refers to the end-of-life process of the turbine.

Researchers conducting lifecycle assessments of wind turbines show that installation is the most materially intense and highest emitting phase of the turbine's lifecycle (Li, Mogollón, Tukker, & Steubing, 2022). There are differences between onshore and offshore wind power generation, where offshore is observed to have a higher impact (7 g CO_2-eq/kWh for onshore and 11 g CO_2-eq/kWh for offshore) due to the greater up-front capital infrastructure (Bonou et al., 2016). The presence of a substation to collect and store generated power is an additional potentially complicating factor (Huang et al., 2017). Though the overall impact of renewables should generally be considered positive given the overall lower impact per unit of energy, one assessment found that the "material requirements per unit generation for low carbon technologies can be higher than for conventional fossil generation: 11-40 times more copper for photovoltaic systems and 6-14 times more iron for wind power plants" (Hertwich et al., 2015, p. 1). This makes end-of-life recycling especially important in reducing overall wind power related impacts. An assessment by Li et al. (2022), for example, found that 6-9% of the cumulative impacts could be reduced by end-of-life recycling and substituting raw materials. Poulsen and Lema (2017) argue in a supply chain analysis of offshore wind farms that planned demand for offshore wind turbines will quickly exceed the capacity of the turbine supply chain. Specifically, the authors identify eight bottlenecks—the overall imbalance between supply and demand—in the offshore market including scarcity of sites, technologies for dealing with intermittency, financial resources, government policies, subsidies and tariffs, human capital and skills, storage capacity for wind energy, and grid expansion and interconnection. Though many of these bottlenecks are less intrusive in an onshore context, many, if not all, still apply, particularly with regards to storage capacity and scarcity of sites.

5. The US context

According to the US Department of Energy, wind energy is expected to be a "cornerstone for achieving U.S. clean electricity generation objectives, including 100% clean electricity by 2035" (DOE, 2022). Former President Biden proposed an offshore wind goal of 30 gigawatts by 2030. The Inflation Reduction Act (touted as the "single largest investment in climate and energy in American history") also added a new loan program—the Energy Infrastructure Reinvestment Program—to "retool, repower, repurpose, or replace energy infrastructure" that has degraded or "improve the efficiency" of existing infrastructure (DOE, 2023). Government support is necessary for developing the wind market and making investments in wind predictable and profitable. To that extent the US uses several tax incentives and subsidies to encourage the development of wind capacity, including the federal Production Tax Credit (Freedonia, 2020b; Marketline, 2020). Up until the Covid-19 pandemic, capacity in the United States was growing significantly with 24.6 billion dollars invested in the sector in 2020. That same year, the US ranked second, behind China, for annual and cumulative wind power capacity additions. As in many other states, growth in the US wind sector is driven by climate goals and commitments. This means two things: first, that when the US backs out of commitments (as it did during the first Trump presidency), the market shrinks; and second (conversely), that so long as the US remains committed to international climate goals (such as limiting global warming to 1.5-2 degrees C), demand will increase exponentially (DOE, 2022).

Research has demonstrated that US wind projects can source 57% (in terms of dollar value) of their components from domestic sources, though this percentage is less for offshore turbines (DOE, 2022, p. 12). Raw and processed materials (nacelles and their generators) are an entirely different matter, as they are produced and shipped globally (mostly from China), and compete with other manufacturing demands. Though domestic production is possible, the wind turbine supply chain remains highly globalized, where producers regularly import whole turbines, and separate major components and subcomponents. US producers import 30% of all towers with year-to-year variation between Spain (18%), Indonesia (27%), and Canada (20%) (DOE, p. 17). Blades are mostly imported from China, Brazil, Mexico, India, and Spain, though Siemens Gamesa has announced plans to open a production facility in Virginia. Primary exporters of nacelles are India, Denmark, Germany, Brazil, and Spain, though 85% of nacelles are assembled domestically (DOE, 2022, p. 17). The concrete used for the foundation is supplied locally, though this only applies for onshore turbines (offshore use a variety of different platforms).

However, the above primary components are composites of numerous subcomponents. All subcomponents, processed materials, and raw materials are broken down in Table 1.

Evidently, the supply chain for wind turbines in the US demonstrates limited domestic capacity and significant dependence on international manufacturers and producers, especially where semiconductors and rare raw materials, such as dysprosium and neodymium, are concerned.

With regards to the end-of-life cycle of wind turbines in the US, some components such as concrete, electrical components, and certain metals can be recycled to a large extent (either completely or as aggregates), whereas others, such as fiberglass, have only limited recycling capacity. No capacity exists in the US for recycling rare earth metals, which is especially notable since demand for these elements is likely to exceed supply in the future (DOE, 2022). Major actors in the wind power market (including Siemens) have announced plans to scale up present recycling capacities. The US Department of Energy (DOE) has also invested in several ongoing projects to advance the end-of-life recycling potential (DOE, 2022).

The DOE has identified several weaknesses and vulnerabilities that production faces in the United States, including "a lack of demand certainty" due to changing political regimes (at federal and state levels) (Doe, 2022, p. 25), a lack of domestic supply chain capacity, geo-political concerns, lack of scale in recycling capabilities, overseas competition for low labor costs, limited education and training, and costly upgrades to existing manufacturing sites and transportation infrastructure. At the time of Joe Biden's presidency, the then administration sought to scale up the production and distribution of wind energy. At that time, the risk was that already existing bottlenecks and constraints would intensify, in some cases exponentially (DOE, 2022, p. 25). With the second Trump presidency, the future is uncertain for supply *and* demand for US wind energy. During his campaign, the then presidential nominee made several promises to cut the inflation reduction act and scrap offshore wind turbines (Milman, 2024). Regardless of whether the Trump administration follows through on either of these promises, supply chains will continue to pose an obstacle to clean energy, even without exacerbated political climates.

Table 1: Sub-components used in US manufacturing of wind turbines and their sources in the global supply chain (information drawn from DOE, 2022, pp. 16–22).

Sub-Components and Materials	**Sources**
Generators	36% percent produced domestically. Imports are from Vietnam, Spain, Serbia, and Germany.
Gearboxes	50% are produced by and shipped from China. Global production is otherwise led by Germany, Spain, Italy, and the United States.
Bearings	Wind turbine specific bearings are sourced from Japan, Germany, and Sweden with some additional domestic production.
Large Castings (rotor hub and nacelle bedplate)	Globally sourced (unspecified).
Forged Rings and Shafts (generator shaft, tower flanges, bearings)	At present, domestic production is sufficient. However, the situation is changing quickly as domestic manufacturing loses market share to foreign labor.
Semiconductors (sensors, power electronics, communicative equipment, etc.)	Almost entirely sourced from East Asia and subject to significant geopolitical risks.
Concrete	Domestic capacity is 100% sufficient.
Steel	12% is imported, however, there is extremely limited capacity for specialty steels such as ‘green’ or ‘electrical.’
Fibre-reinforced composites (glass and carbon fibre for blades and nacelle cover)	Sourced from sectors that include aerospace, automotive, and marine applications.
Polymers (resins in composites, coatings, etc.)	Petrochemical feedstocks.
Rare earth magnets	Entirely imported, mostly from China.
Rare-earth elements (neodymium and dysprosium)	Entirely imported, mostly from China.
Steel alloying elements (chromium, molybdenum, manganese, nickel, and niobium)	Extremely limited domestic quantities.
Balsa Wood (widely used for blades as lightweight core material. Substitutes can include PTE, PVC, or foam, all concerns from a sustainability standpoint)	Imported from states near the equator.

6. Analysis

With regards to supply chain management, Siemens Energy, which includes Siemens Gamesa Renewable Energy, require its suppliers to uphold a code of conduct concerning human rights, fair operating practices, labor practices, and environmental protection (Siemens Gamesa, n.d.-a, n.d.-b, 2019a, 2019b). Ignoring for the moment whether Siemens' method of self assessment questionnaires is sufficient for monitoring supplier sustainability (Siemens Gamesa, 2019a, p. 5), the existence of such policies minimally implies an intent to monitor sustainability throughout the supply chain. However, even if Siemens' supply chain policies *were* effective, would this matter from a degrowth perspective?

There are eleven minerals involved in the manufacturing of wind turbines, two of which are rare earth minerals required to produce permanent magnets (neodymium and dysprosium). Wilburn (2011) estimates that meeting 20% of US electricity demand by 2030 would require 1.5 million metric tons of steel, 310,000 metric tons of cast iron, 40,000 metric tons of copper, and 380 metric tons of neodymium. The problem is also not particular to wind power—solar fares no better in terms of material footprint. In a report, the World Bank wrote that:

> *the technologies assumed to populate the clean energy shift (wind, solar, hydrogen and electricity systems) are in fact significantly MORE materially intensive in their composition than current traditional fossil-fuel-based energy supply systems (57).*

Five years later, the International Energy Agency (IEA) reiterated the World Bank's conclusions:

> *A typical electric car requires six times the mineral inputs of a conventional car, and an onshore wind plant requires nine times more mineral resources than a gas fired power plant. Since 2010, the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as the share of renewables has risen (5).*

Neither of these organizations explicitly argue for degrowth as a necessary strategy for mitigating the impact of an economy that continues to compound energy demands year after year. Yet, popular degrowth policies such as a tax on industrial energy consumption (Alexander, 2012, 2013; Alier, 2009; Capellán-Pérez et al., 2015; Cechin & Pacini, 2012; Fitzpatrick et al., 2022; Gunderson et al., 2018; Huppes & Ishikawa, 2009; Johanisova & Wolf, 2012; Latouche, 2005, 2009b; Petersen et al., 2019); targeted reductions of energy consumption and waste by a factor of 4 (Negawatt scenario), total primary energy supply by 10% on 2015 levels, and total energy consumption in the Global North by 70% by 2050; and the equitable sharing of total primary energy supply, should be considered as viable pathways for constraining increasing demands for new sources of renewable energy (Alexander, 2017; Alexander & Gleeson, 2018; Garcia et al., 2018; Kallis et al., 2020; Latouche, 2009a; Mastini et al., 2021; Nelson & Schneider, 2019; Stuart et al., 2022).

Of course, claims such as these must be measured against assessments considering the bulk (total) material intensity over the technology's lifecycle. Nijnens et al. (2023), for instance, argue that the "mass of minerals demanded for the energy transition technologies is a fraction of the mass of coal produced in the current fossil-dominated energy system" (p.2410). Specifically, Krane et al. (2021) "demonstrate that installing just 1 GW of wind capacity to replace coal on a grid like that in Texas reduces total mining by 25 million tonnes over 20 years." (p.7) Similarly, Bai et al. (2023) show through a multi-dimensional dynamic analysis of sustainable transitions in Guangdong province, China, from 1978 to 2018 (and abstracted out to 2050), that renewables increase embodied emissions (e.g., concrete) but reduce emissions overall. The point though, from a degrowth perspective, is *not* whether or not the overall impact is *lower* for renewable energy sources in an expanding economy with increasing energy demands, but whether the scale of the economy can be constrained relative to gains made by lower impact renewable sources of energy. Otherwise, the analysis reverts back to debating the degree of relative material decoupling. This is also noted in the industrial ecology literature (Wiedenhofer et al., 2021). Thompson (2023) observes that instead of replacing fossil fuels, renewables added to new energy demands, concluding that the adoption of renewables must be accompanied by major changes in policy (e.g., ending fossil fuel subsidies). The point is also *not* to diminish the necessity of transitioning to renewables but to demonstrate why, from a degrowth perspective, the growth of energy demand must be mitigated using the above policies, alongside the transition to renewable energy.

According to the IEA, global wind capacity has quadrupled in a decade due to falling costs, and this trend is likely to continue exponentially for several more decades (IEA, 2022, p. 20; see also: Lowe & Drummond, 2022). This is particularly true for offshore turbines, which have otherwise lagged behind onshore production and are likely to triple growth in the rare earth minerals market by 2040 (IEA, 2022, p. 66). As the authors of the report remark, “the prospect of a rapid increase in demand for critical minerals – well above anything seen previously in most cases – raises huge questions about the availability and reliability of supply” (IEA, 2022, p. 11), echoing observations made across the industrial ecology literature (Farina & Anctil, 2022; Kalt et al., 2022; Lee et al., 2024; Li, Mogollón, Tukker, Dong, et al., 2022; Liang et al., 2022; Northey et al., 2023). According to Liang et al. (2022), following a review of the literature, “most articles conclude that material constraints may become a stumbling block to the energy transition” (p.7). Making the situation worse is the high geographical concentration of production, the length of time required to plan and begin projects, declining resource quality, increasing concern over environmental and social consequences of resource extraction, and higher exposure to climate risks (particularly where water stress is a concern). The IEA report concludes with caution that “these risks are… manageable, but they are real” (IEA, 2022, p. 12). Supply chain due diligence and management, such as those implemented by Siemens, are indeed necessary but may be insufficient.

The above concerns the minerals directly implicated in the manufacturing of wind turbines. However, given that the only use for dysprosium and neodymium is in the production of permanent magnet generators, a simple substitution of permanent magnet generators for geared generators may seem like a sufficient solution. However, geared turbines are less reliable and thus more prone to malfunction (especially at low temperatures to which they would be exposed in offshore scenarios) which means more repairs, more maintenance, and less reliable supplies of energy. But even if producers could avoid permanent magnet generators, wind turbines are also indirectly implicated in the market of *another* non-renewable mineral: lithium. Massive energy storage grids will increasingly attend projects such as RWF. In 2017, RWF completed the Texas Wave project to develop lithium battery storage capacities. According to Mark Frigo, VP of Energy Storage North America at E.ON, "[t]he battery energy storage systems will be an integral part of the wind farm facilities near Roscoe” (Newswire, 2017). Of course, some areas, such as offshore, are more likely than others to sustain steady and high wind speeds, but those require unsustainable quantities of neodymium and dysprosium. Some degree of energy storage will be necessary, and as fewer sites have the elevation for hydraulic storage, lithium battery storage is becoming the inevitable solution.

Three rare minerals are essential to the development of wind energy capacity: dysprosium, neodymium, and lithium (copper faces similar stresses, but to a lesser extent). The most notable aspect of the first two rare earth minerals is that extraction and supply is entirely dominated by China, a fact of growing concern to its non-allies such as the United States. The issue here is not so much neo-colonial, as it is geo-political, the concern being to what extent such supply chains will remain reliable/tenable in the future. Microprocessors used in the sensors and other electronics on the turbine face similar tensions and risks. Lithium, on the other hand, raises different questions. The IEA notes that “Lithium demand for clean energy technologies is growing at the fastest pace among major minerals” (IEA, 2022, p. 139). This time, the issue here *is* neo-colonial. The report from the world bank notes that “[n]onrenewable mineral resources play a dominant role in 81 countries that collectively account for a quarter of world GDP, half of the world’s population, and nearly 70 percent of those in extreme poverty” (World Bank Group, 2017, p. 26). Consequently, the extraction of non-renewable resources will play a dominant role in the future of mineral rich countries. The World Bank is optimistic about the potential benefits to be accrued by such states, however, in the same paragraph they also note that the necessary infrastructure of such projects “carry significant up-front capital costs” (World Bank Group, 2017, p. 26). For a degrowth perspective critical of the potential for neocolonial extraction under the guise of green growth, the concern is *not* whether the rare minerals in question will be mined, but rather how the profits are distributed and the degree of autonomy possessed by those who will bear the brunt of extraction. Essentially, to what extent can states lacking the necessary infrastructure acquire it on favorable terms. Numerous scholars are already concerned about the colonial structures of dependency and exploitation that are reproduced along these new commodity frontiers (Altamirano-Jimenez, 2021; Bazhanov, 2022; Jerez et al., 2021), including those specifically writing from a degrowth perspective (Andreucci & Kallis, 2017; Hickel, 2019a, 2019b, 2021b).

First, it is imperative that would-be neocolonial economies in the Global North scale down local energy demands. The policies proposed above that include caps on energy consumption and waste are a start, but they should be framed within a wider discussion of the Global North's ecological debt that responds to the Global South's demands for fair climate compensation (Dagres, 2023). Canceling odious debt and debt moratoriums and a strict global minimum corporate tax are two key policies to these ends that should supplement general reparations for ecological debt (including but not exclusive to biopiracy, and carbon, corporate, and waste debts) (Fitzpatrick et al., 2022). At the same time, economic autonomy (local democratic ownership of the resources) must be fostered in communities at the frontiers of new green extraction, in global *and* local contexts (Bell, 2014; Latouche, 2009a; Mastini et al., 2021; Nørgård & Xue, 2016; Trainer, 2012). From a degrowth perspective, policy should begin from two ends: (1) decreasing energy demands in the global North, and (2) increasing economic autonomy in the South, and should converge on an overall reduction in global neo-colonial extraction (Hickel, 2021b; Sultana, 2022). Furthermore, the North-South dichotomy must not distract from the neocolonial extraction occurring on settler-occupied territory. For example, in Canada, where colonial governments are turning their gaze to rare earth mineral deposits located on territory long-protected by the Marten Falls First Nation, the Webequie First Nation, and the Neskantaga First Nation (amongst several others including the Nibinamik First Nation and Long Lake 58 First Nation), the only legitimate policy, from a degrowth perspective, is that which respects Indigenous land and traditions (Alook et al., 2023; Casey, 2023).

7. Conclusion

From a degrowth perspective, renewable sources of energy, such as wind, are necessary but insufficient for mitigating ecologic instability. Once installed, wind turbines produce zero emissions and produce energy that can be integrated into utility scale grids. However, installing turbines is not a permanent solution as upgrades and replacements are inevitable and, at present, major components are not recyclable. Manufacturing present and future turbines exponentially increases demand in an already pressurized minerals market, particularly for copper, dysprosium, neodymium, and lithium. The problem is the increasing scale of energy demand and a global economic system that leaves no stone unturned (or resource un-extracted) in its search for new streams of revenue and value, plunging an earth already pushed past disequilibrium deeper and faster into crisis. Specific policies such as a minimum global corporate tax and caps on energy consumption and waste in the Global North can address this problem in a specific capacity. However, a broader coordinated degrowth strategy, such as those proposed by Parrique (2019) and Schmelzer et al. (2022), is necessary to ensure gains in renewable energy are not undercut by the increasing scale of the economic system.

Wind farms, like the Roscoe Wind Farm, must form part of a more general strategy of maintaining present capacity while reducing future demand for total energy output in affluent states. At the policy level, this can be achieved with a tax on industrial energy consumption, targeted reductions of energy consumption and waste (including caps and bans) and immediately terminating laws that grant companies access to territory protected and governed by Indigenous peoples. Other steps include shifting away from the current model of production which favors companies and private infrastructure and moving towards community renewable energy projects funded through new tax revenue streams (Diesendorf and Taylor, 2023). Regarding supply chains, allowing companies to self-report is untenable; real public oversight (either as a specific commission or committee) is needed.

Of course, the difficult part of any degrowth-inspired approach to energy policy is that the whole picture must be considered. It is impossible to discuss a particular industry without placing it in the context of total energy demand and resource extraction; canceling odious debt and debt moratoriums are not extrinsic to energy policy, but necessary guarantees that the consequences of reduced energy demand and energy supply are not born out by the Global South. The same is true for the local context, especially in places with stark inequality (like the United States). This means that universal basic services (housing, education, health, transport, recreation, libraries, etc.), job training to strengthen domestic manufacturing capacities, wealth and progressive income taxes, are also necessary here, as they would be to any other discussion of a degrowth politics (Diesendorf and Taylor, 2023). Most of these policies could be implemented *today* in the United States. Obviously, they will not be without intense pressure and mobilization from NGO's and citizens. This paper thus primarily functions as a mapping of some strategic leverage points. At any rate, the path forward cannot be a blind substitution of 'green energy' but must incorporate the above critique with an over-arching strategy that aims to decrease demand and dependency upon excessive use of energy altogether.

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