Strengthening clean energy supply chains for decarbonisation and economic security

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Strengthening Clean Energy Supply Chains for Decarbonisation and Economic Security

OECD Report for the G7 Finance Ministers
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The development of secure and competitive supply chains in clean energy technologies is critical to ensure a resilient clean energy transition and energy/economic security. All G7 members have made the adoption of clean energy technologies a central part of their strategy to move towards net zero emissions. Yet today's clean energy supply chains face several security concerns – notably (but not limited to) the high dependence on imports from individual countries and firms in key stages of clean energy supply chains – which need to be better understood and addressed to prepare for a decarbonised future. There is also a need to better comprehend the implications of policies that countries implement to securitise clean energy supply chains.

This report contributes to the discussion in three ways. First, it maps the degree of geographical and market concentrations at different stages of key clean energy supply chains – electrical vehicle (EV) batteries, solar photovoltaic (PV) panels, and wind turbines – to identify potential security risks. Second, it showcases the existence of a policy trilemma between *clean energy adoption*, *supply chain securitisation*, and *competitive neutrality* in clean energy supply chains. Third, it provides suggestions on the effective use of public finance tools by G7 members to build resilient and inclusive clean energy supply chains for decarbonisation.

MAPPING SUPPLY CHAIN VULNERABILITIES

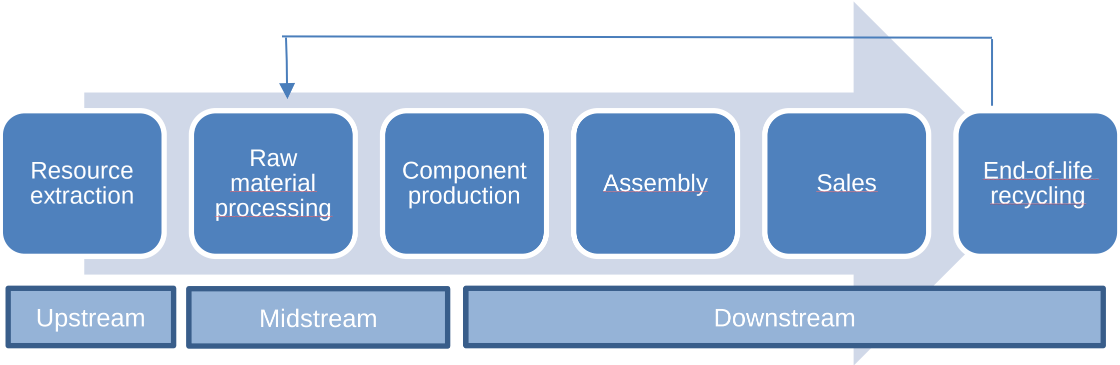
Global value chain analysis can be used to study the main vulnerabilities and comparative advantages that G7 countries face in the supply chains of EV batteries, solar PV panels, and wind turbines. Specifically, such analysis can break down these supply chains into their component elements and use publicly available data to identify the degree of geographical and market concentration.

While there are substantial differences in the supply chains of EV batteries, solar PV panels and wind turbines, the same six supply chain stages can be used to conduct relevant analysis (Figure 1). *Upstream* consists of the stage of resource extraction. *Midstream* covers raw material processing and the production of certain components. *Downstream* covers the manufacturing of more built-up components, assembly, sales, and end-of-life recycling.

This paper focuses on the degree of geographical and market concentration in each production stage since these are two factors that influence the security risks that a country faces in clean energy supply chains. Chokepoints emerge in a global supply chain when a country or firm have such a strong control over specific stages that a reduction in their supply can endanger the entire supply chain for other countries. Geographical concentration, which in this study is operationalised with the production share of the three largest economies, can help determine such a chokepoint by identifying the degree to which its supply is vulnerable to country-specific disruptions such as natural hazards or geopolitical events. Market concentration, which is measured with the market share of the three largest firms, also helps identify chokepoint risks related to collusion, price fixing and dumping.

Analysis is conducted separately for the supply chains of EV batteries, solar PV panels, and wind turbines, before concluding the section with a discussion of the overall insights.

Figure 1. Global value chain analysis of clean energy technologies



1. Electrical vehicle batteries

EV batteries are at the heart of G7 countries' clean energy transition, with all members striving to ensure that the majority of new passenger car sales are no longer petrol or diesel-powered by 2030 or sooner. Analysis therefore starts by studying the degree of geographical and market concentration across the five main production stages of the EV battery supply chain: resource extraction, raw material processing, cell component production, battery cell/pack production, EV production, and recycling (the report does not analyse the non-production stage of sales).

Table 1 summarises the key findings. Most production stages in EV battery supply chains have high geographical concentrations (i.e. more than 70% of global production concentrated in the three leading countries), that China plays a dominant role in the middle stages of the supply chain (raw material processing and component production), and that China competes with Japan and Korea in the downstream stages. The market concentration data are incomplete but show medium levels of market concentration across different stages of the EV battery supply chain with a growing importance of Chinese firms.

Table 1. Characteristics of the EV battery supply chain

Supply chain segment		Largest producers	Geographical concentration (G-CR3)		Market concentration (M-CR3)	
Resource extraction*	Lithium	AUS (55%), CHL (26%), CHN (14%)	95%	High	49%	Medium
	Cobalt	COG (71%), RUS (4%), AUS (3%)	78%	High	42%	Medium
	Nickel	IDN (37%), PHL (14%), RUS (9%)	60%	Medium	19%	Low
	Manganese	ZAF (37%), GAB (18%), AUS (16%)	71%	High	NA	NA
	Graphite (natural)	CHN (82%), BRA (7%), MOZ (3%)	92%	High	NA	NA
Raw material processing**	Lithium	CHN (58%), CHL (29%), ARG (10%)	97%	High	NA	NA
	Cobalt	CHN (65%), FIN (10%), BEL (5%)	80%	High	NA	NA
	Nickel	CHN (35%), IDN (15%), JPN (8%)	58%	Medium	NA	NA

Supply chain segment		Largest producers	Geographical concentration (G-CR3)		Market concentration (M-CR3)	
	Manganese	CHN (93%)	93%	High	NA	NA
	Graphite (natural)	CHN (close to 100%)	100 %	High	NA	NA
Component production ***	Cathode	CHN (53%), JPN (21%), KOR (20%)	94%	High	55% (CR7)	Medium
	Anode	CHN (78%), JPN (16%), KOR (4%)	98%	High	50% (CR4)	Medium
	Separator	CHN (66%), KOR (16%), JPN (12%)	94%	High	50% (CR5)	Medium
	Electrolyte	CHN (62%), KOR (14%), JPN (11%)	87%	High	NA	NA
Assembly ***	Battery cell/pack	CHN (79%), USA (6%), HUN (4%)	89%	High	69%	Medium
Recycling	Recycling	CHN (58%), GER (15%), FRA (7%)	80%	High	NA	NA

Note: High>70%; medium if >40% and <70%; low if<40%.
* Data from the United States Geological Survey to calculate geographical concentration for 2021.
** Data from the International Energy Agency (2022b) and Benchmark Mineral Intelligence to calculate geographical concentration for 2019.
*** Data from BloombergNEF (2021a) to calculate geographical concentration for 2020.

Resource extraction

Lithium-ion batteries used in EVs require a significant amount of critical minerals. A single car lithium-ion battery pack contains around 8kg of lithium, 35kg of nickel, 20kg of manganese, 14kg of cobalt, and significant amounts of graphite (Melin et al., 2021).

Data from the US Geological Survey shows that most critical minerals used in EV batteries have a high geographical concentration ratio, that they are mostly extracted in traditional mineral-abundant countries, and that G7 countries are minor players in the resource extraction production stage. In 2021, the geographical concentration ratio exceeded 70% for four critical minerals: lithium, graphite, cobalt, and manganese. Chokepoint risks appear especially large for lithium and graphite for which the geographical concentration ratios exceeded 90% and for cobalt where Congo has 78% of the global production share in 2021.

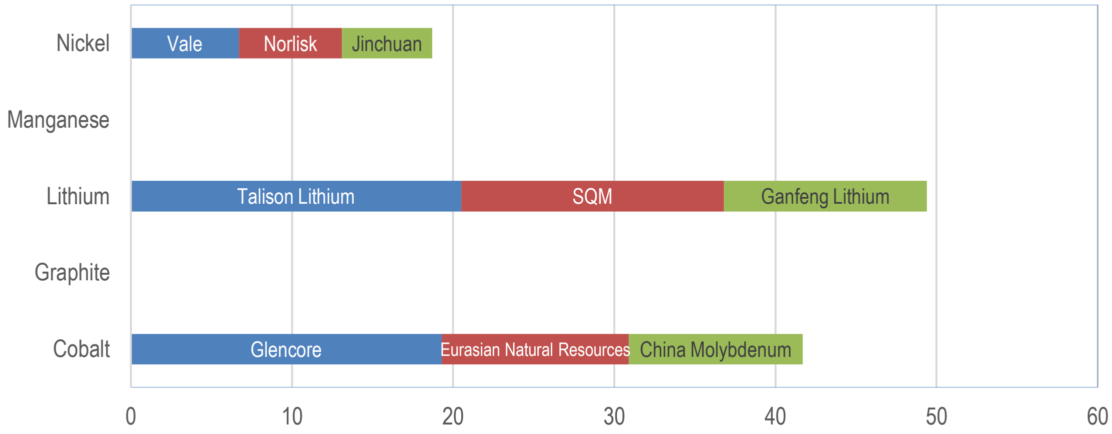
It was only possible to calculate market concentrations for lithium, cobalt, and nickel due to limited market information for manganese and graphite. The market concentrations were medium for lithium and cobalt mining and low for nickel mining, even though it has increased over time among other things due to efforts by China to beef up ownership and control of critical minerals that are used in EV batteries (Figure 2).

For lithium, the share of the top three companies in global production was 49% in 2020. China-owned Talison Lithium was the market leader with a share of 21%. Lithium mines are generally incorporated where they are located even though China's Talison (majority-owned by Tianqi) and Ganfeng have made important inroads in mineral-abundant countries.

For cobalt, the share of the top three companies in global production was 42% in 2020. Swiss-based Glencore was the market leader with a market share of 19%. Although the vast majority of cobalt production originates in Congo, firms incorporated there exploit only 3.5% of global output. China has made major inroads in Congo's cobalt mining sector and currently controls (owns or finances) 15 of the 19 cobalt-producing mines in Congo. These mines account for half of Congo's recent cobalt mining production. Because of this vast presence in Congo, Chinese firms own about 24% of the known global cobalt mine production (Gulley et al., 2019).

For nickel, the share of the top three companies in global production was 19% in 2020. Brazil's Vale is the market leader with a share of 7%. The country of incorporation of mining companies exploiting nickel is more dispersed than the country of production, except in the Philippines, where a Filipino mining company exploits nickel.

Figure 2. Share of top three companies in global production, 2020



Source: Leruth et al. (2022).

Raw material processing

Batteries require high purity materials. Therefore, significant refining is required for critical minerals to reach sufficient quality battery chemical precursors that can be used for EV battery supply chains.

Calculations using data from the International Energy Agency (2022b) and Benchmark Mineral Intelligence suggest that the geographical concentration ratio for raw material processing in 2019 was high for all critical minerals except nickel, with most refining occurring outside of the region where the minerals were extracted.[1] The geographical concentration ratio was especially high for lithium, manganese, graphite, and cobalt where it exceeded more than 80%. For all critical minerals used in EV batteries, China was the dominant market leader. The chokepoint risk was especially large for the refining of manganese and graphite were China's global production share exceeded 90% in 2019.

Data provided by Leruth et al. (2022) suggest that the market concentration in cobalt and lithium refining was medium. In cobalt refining, the market is predominantly controlled by Chinese companies. In China, Jinchuan Group, Zhejiang Huayou Cobalt, and Shenzhen GEM are the largest refining players. Examples of refining operations outside of China are few. Umicore, a Belgian group, owns the Kokkola refinery in Finland and Eramet has a small facility in France. Glencore has also

[1] Indonesia's decision in 2019 to restrict exports of raw nickel ores and to introduce domestic processing requirements helps explain the lower geographical concentration ratio for nickel processing.

invested in First Cobalt, which could result in cobalt sulfate refining operations in Canada in the future. Sconi could also seek to expand cobalt sulfate production at a plant in Australia. In lithium, five major companies are responsible for three-quarters of global production capacity.

Cell component production

About 21% of the value added of a finished lithium-ion battery pack comes from the cell stage of production (Argonne National Laboratory, "Batpac 4.0", 2019). To produce electricity, lithium-ion batteries shuttle lithium ions internally from one layer, called the anode, to another, the cathode. The two are separated by another layer, the electrolyte.

Analysis of data from BloombergNEF (2021a) suggests that in 2020 the geographical concentration ratio for midstream components was high, approaching or exceeding 90%, with China dominating in all categories. Korea and Japan also held significant market shares in these components, highlighting the dominance of East Asia in cell component production.

Market concentration in the components is medium, dominated primarily by Chinese, Korean and Japanese firms. Seven companies were responsible for 55% of global cathode material production capacity, including Sumitomo (Japan); Tianjin B&M Science and Technology (China); Shenzhen Dynanonic (China); and Ningbo Shanshan (China).

Four companies were responsible for half of the global anode production capacity, including Ningbo Nanshan (China); BTR New Energy Materials (China); and Shanghai Putailai New Energy Technology (China). The top six are all Chinese and account for two thirds of global production capacity.

Separators production was also concentrated with five companies responsible for half of the global production capacity. Key players include Zhuhai Enjie New Material Technology (China); Shanghai Putailai New Energy Technology (China); and SK IE Technology (Korea).

Battery cell/pack production

Data from BloombergNEF (2021a) illustrate China's dominance in lithium-ion battery cell capacity. In 2021, China was responsible for 79% of global Li-ion manufacturing capacity (GWh), leaving the numbers two and three far behind (United States S 6.2%; Hungary 4%).

In 2021, the market concentration in battery cell production was medium, with the top-three producers accounting for 69% of global production capacity. CATL (China) 's global share of lithium-ion production capacity stood at 32%, LG Energy Solution (Korea) had a share of 22%, and Panasonic (Japan) had a share of 15%.

Recycling

Industry experts consider the recovery of materials from retired EV batteries as an important alternative source to mining (Moisé & Rubinova, 2023). The materials recovered through battery recycling can replace future material supply that would otherwise need to be extracted from the earth to meet demand. Currently, however, only 5% of EV batteries are recycled (Baum et al., 2022). And despite several efforts around the globe to develop enriched recycling programs, it is expected that by 2040 recycling will reduce mineral supply requirements by around 10%.

China is the global leader in recycling of lithium-ion batteries, far outpacing all other nations. As of late 2021, China's global share of EV battery recycling capacity was 58%, almost four times larger than Germany (15%) and more than eight times larger than France (7%).

Automotive OEMs are increasingly creating recycling & supply agreements with specialised EV battery recyclers (e.g. CATL, Li-Cycle, Northvolt).

2. Solar photovoltaic panels

Table 2 summarises the analysis of geographical and market concentration in the supply chain of solar PV panels. The main findings are that the geographical concentration is high for bauxite mining and polysilicon processing where geographical concentration is high. Geographical concentration in component production and assembly is very high and is dominated by China. G7 countries play a limited role in the supply chain of solar PV panels. Market concentration is low in the upstream production stages but turns to medium in midstream and downstream production stages.

Table 2. Characteristics of the solar PV panel supply chain

Supply chain segment		Largest producers	Geographical concentration (G-CR3)		Market concentration (M-CR3)	
Resource extraction*	Copper	CHL (27%), PER (10%), CHN (8%)	46%	Medium	24%	Low
	Bauxite	AUS (28%), CHN (22%), GIN (22%)	72%	High	NA	NA
	Silver	MEX (23%), CHN (14%), PER (13%)	50%	Medium	31%	Low
Raw material processing **	Copper	CHN (38%), CHL (8%), JPN (6%)	53%	Medium	NA	NA
	Aluminium	CHN (57%), RUS (6%), CAN (5%)	69%	Medium	NA	NA
	Polysilicon	CHN (81%), GER (8%), KOR (3%)	92%	High	51%	Medium
Component production **	Wafer	CHN (53%), JPN (21%), KOR (20%)	91%	High	59%	Medium
	Cell	CHN (78%), JPN (16%), KOR (4%)	98%	High	34%	Low
Assembly **	PV module	CHN (80%)	80% (CR1)	High	41%	Medium
Recycling	Recycling	NA	NA	NA	NA	NA

High>70%; medium if >40% and <70%; low if<40%.
* Data from the United States Geological Survey to calculate geographical concentration for 2021.
** Data from the International Energy Agency (2022c) to calculate geographical concentration for 2019.

Resource extraction

While solar panels use the nearly infinite power of the sun to create renewable energy, a variety of non-renewable minerals that are mined from the earth make up the physical components of these green power systems, including copper, bauxite, and silver.

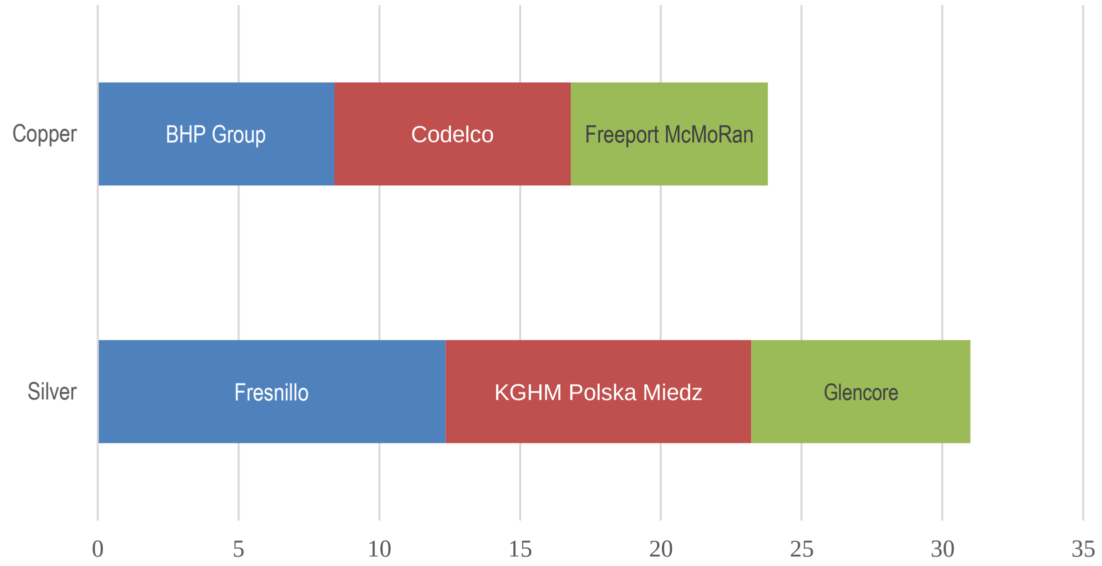
Data from the US Geological Survey suggest that the geographical concentration ratio of bauxite was high where it stood at 72% in 2001. It was medium for copper and silver where the geographical concentration ratios were 46% and 50% respectively.

The market concentration ratios remained relatively low for copper and silver (Figure 3). Recent data were insufficient to calculate market concentration for bauxite.[2] For copper, the share of the top

[2] Rio Tinto, Alcoa, South32 and Chalco are global market leaders in bauxite mining.

three companies in global production was 24% in 2020. UK-based BHP Group was the market leader with a market share of 8.4%. For silver, the share of the top three companies in the global production of the top twenty firms was 31% in 2021. Mexican-owned Fresnillo was the market leader with a share of 12%.

Figure 3. Share of top three companies in global production, 2020 and 2021



Source: Leruth et al. (2022) and https://www.statista.com/statistics/253327/leading-silver-producing-companies/.

Raw material processing

Data provided by the International Energy Agency (2022c) is used to determine the 2021 geographical concentration for raw material processing in solar PV panel supply chains. It ranged between medium and high, with most refining occurring outside of the country or region where the minerals were mined. China was the leader in production capacity in all categories of material processing. The chokepoint risk is especially high for polysilicon where the share of the top three countries in global production was 92% in 2021. China was the dominant leader in polysilicon processing with a global share of 81%.

The International Energy Agency (2022c) showed that the market concentration for polysilicon in 2021 was medium at 51%. The leading producer of polysilicon, Tongwei, had a market share of 19%, followed by the two other Chinese companies GCL Technology and Daqo New Energy.

Component production and assembly

The geographical concentration ratio for key components in solar PV panel manufacturing was high in 2021, and China has developed into the leading producer in all categories of component production and assembly (International Energy Agency, 2022c). In 2021, China's share in global production for PV modules, cells and wafers was 80%, 78% and 53% respectively.

Market concentration in the production of components and assembly was medium. Data from the International Energy Agency (2022c) show that the top three companies' share of total capacity is 59%, 34% and 41% for wafers, cells and PV modules respectively. While Jinko, LONGi and

Canadian Solar are large global players, the information available was insufficient to calculate market concentration in these categories.

Recycling

Only 10% of solar PV panels are currently recycled, and rarely by specialised recycling companies. The high cost of recycling makes it cost ineffective to recycle solar PV panels without government mandates. In the United States, for example, solid waste landfills typically charge USD 1 to USD 2 to accept a solar panel, rising to around USD 5 if the material is deemed hazardous waste. By contrast, recycling solar panels costs about USD 18 per panel.

The EU was the first major region that holds PV module installers accountable for their e-waste and requires solar producers to recycle and pay an upfront recycling fee through an organisation called PV Cycle. It falls under the EU's Waste Electrical and Electronic Equipment Directive, an extended producer programme that mandates that manufacturers of electronic equipment, including solar panels, contribute to a fund that is used to subsidise disposal.

The global solar panel recycling market is fragmented due to the presence of numerous players. One of the major companies is Veolia (France) that in 2018 has opened the first recycling line developed specifically for recycling solar panels. First Solar appears to be the only US panel manufacturer with an up-and-running recycling initiative, which only applies to the company's own products at a global capacity of two million panels per year. Reclaim PV Recycling provides solar PV recycling options in Australia.

3. Wind turbines

Wind turbines are heavy, bulky products. They are largely made of concrete (onshore) or steel (offshore), and consist of multiple large components such as nacelles, blades and towers, making them costly to transport. As a result, wind turbine supply chains tend to be concentrated near large demand centres such as China, the United States and India.

Taking a deeper dive into the supply chains of wind turbines nonetheless shows that geographic concentration varies across supply chain segments. Table 3 summarises the key findings geographical and market concentration analysis. Most production stages in wind turbine supply chains have medium geographical concentrations (between 30% and 70% of global production concentrated in the three leading countries).This can be attributed to the fact that the wind turbine market is globally bifurcated. Chinese-dominated supply chains produce mostly for China; G7-dominated supply chains produce mostly for G7. The only four exceptions are rare earth mining, rare earth processing, nacelles, and blades where the geographical concentration ratio was high, and where China played a more dominant role. The market concentration data are highly incomplete, making it difficult to assess the chokepoint risks related to it.

Table 3. Characteristics of the wind turbine supply chain

Supply chain segment		Largest producer	Geographical concentration (G-CR3)		Market concentration (M-CR3)	
Resource extraction*	Zinc	CHN (32%), PER (12%), AUS (10%)	55%	Medium	NA	NA
	Copper	CHL (27%), PER (10%), CHN (8%)	46%	Medium	24%	Low
	Rare earth	CHN (60%), USA (15%), MMR (10%)	85%	High	73%	High
Raw material processing**	Zinc	NA	NA	NA	NA	NA
	Copper	CHN (38%), CHL (8%), JPN (6%)	53%	Medium	NA	NA
	Rare earth	CHN (90%)	90%	High	NA	NA
Component production***	Nacelle	CHN (58%), USA (10%), IND (10%)	77%	High	NA	NA
	Blades	CHN (59%), IND (12%), USA (5%)	76%	High	NA	NA
	Towers	CHN (49%), ESP (10%), USA (8%)	69%	Medium	NA	NA
	Generators	CHN (38%), IND (10%), ESP (8%)	56%	Medium	NA	NA
	Gearbox	CHN (46%), GER (14%), ESP (12%)	72%	Medium	NA	NA
Assembly****	Wind turbine	CHN (40%), USA (16%), GER (8%)	64%	Medium	36%	Low

High>70%; medium if >40% and <70%; low if<40%.
* Data from the United States Geological Survey to calculate geographical concentration for 2021.
** Data from the International Energy Agency (2002c) to calculate geographical concentration for 2021.
*** Data from BloombergNEF (2021) to calculate geographical concentration for 2020.
**** Data from IRENA (2022) to calculate geographical concentration on installed wind power capacity for 2020.

Resource extraction

Critical minerals including copper, zinc and rare earth metals are widely used in wind turbines. While the degree of geographical concentration is medium for copper and zinc, it is high for rare earths which are widely used in the permanent magnet generators of wind turbines. According to data from the US Geological Survey, the geographical concentration ratio stands at 85%, with China being responsible for 60% of global extraction.

While there is limited information about global firm market shares, China's decision to consolidate the rare earth industry since 2018 implies that the degree of market concentration in rare earth resource extraction is high and dominated by large Chinese State-Owned Enterprises (SOEs). The largest two SOEs are China Northern Rare Earth Group High-Tech Co. Ltd. and China Rare Earth Group Co. Ltd. which dominate global rare earth production and processing.

Raw material processing

Data provided by the International Energy Agency (2022c) suggest that the 2021 geographical concentration for copper processing was medium and for rare earth metals was high. The latter according to some sources amounts to up to 90% and is dominated by the two Chinese SOEs China Northern Rare Earth Group High-Tech Co. Ltd. and China Rare Earth Group Co. Ltd.[3]

Component production

The geographical concentration ratio of key wind turbine components ranges from medium to high according to data from BloombergNEF (2021), with China occupying the largest share for each component. The geographical concentration ratio for nacelles, blades and gearboxes exceeded 70% in 2020, with China in all three cases approaching or exceeding 50% of global manufacturing capacity. For towers, generators and gearbox, the geographical concentration ratio was medium and China's global production share was below 50%.

China's high global share for different components is likely due to the disproportionately large size of China's market. Typical onshore wind projects generally have a large domestic content share. BloombergNEF (2021) estimates that a typical onshore wind project in the United States sources 57% of its components (by dollar value) domestically. The US Department of Energy (2022) estimates that domestic content exceeds 85% in nacelle assembly, between 60-75% for wind towers, and between 30-50% for blades and hubs. The lower domestic content for blades is due to its labour-intensive process, pushing OEMs to offshore their production to countries like China, India, Mexico and Turkey for both regional and global demand (USITC, 2022). The domestic content share of the different components in wind turbines is not known for other G7 countries.

It is more difficult to determine the market concentration for the various components. Especially outside China, most turbine makers are sufficiently vertically integrated to use blades and other components that are produced in-house. In China, there is a wider use of independent blade suppliers.

Turbines

In terms of installed wind power capacity (MW), the global industry is dominated by the world's largest economies. In 2021, China was the market leader with a share of 40%, followed by the United States (16%) and Germany (8%). Together, the world's three largest market accounted for 64% of global installed wind power capacity, suggesting a medium level of geographic concentration. China's dominant share is largely due to strong local demand, which is substantially larger than in G7 countries.

In terms of market concentration, the global market of wind turbines has limited concentration, with the top three companies – Vestas (Denmark), Goldwind (China) and Siemens Gamesa (Germany) – only accounting for 36% of the total commissioned wind capacity in 2021. These numbers, however, obscure higher levels of concentrations in specific regions. In 2020, the four Western firms, Vestas (34% of installations outside of China), GE (28%), Siemens Gamesa (11%) and Nordex (7%)—accounted for 80% of installations outside of China. Within China, the market was more fragmented and dominated by state-owned conglomerates with deep pockets and strong manufacturing capabilities. In 2021, Goldwind, Envision and Windey accounted for 48% of China's total market capacity, focusing almost entirely on their home market. This is largely because the Chinese market remains all but closed to foreign companies (Lacal-Arantegui et al., 2019).

[3] https://www.china-briefing.com/news/china-merges-three-rare-earths-state-owned-entities-to-increase-pricing-power-and-efficiency/

Recycling

Siemens Gamesa Renewable Energy launched the first fully recyclable blade in 2021, with a new resin that can be more easily separated to recover materials.

While some parts of wind turbines are completely recycled (e.g. metals, electronic components), some have limited recycling options (e.g. wind turbine blades) and some are not recycled (rare earths).

4. Overall assessment

This analysis has unveiled substantial geographical and market concentrations in all three of the clean energy supply chains, which could point to security or chokepoint risks. Specifically, the analysis has identified several production stages with higher risks and vulnerabilities in clean energy supply chains:

- In EV batteries, most production stages have high geographic concentrations, China plays a dominant role in middle stages (raw material processing and component production), and competes with Japan and Korea in downstream stages.
- In solar PV panels, China dominates the middle and downstream stages (polysilicon, component production and assembly), and G7 countries play a limited role.
- In wind turbines, risks are lower due to a bifurcated global market. Chinese-dominated supply chains produce mostly for China; G7-dominated supply chains produce mostly for G7, while China dominates key rare earth production for permanent magnets.
- Recycling in the three industries remains in its infancy and will need to expand significantly to reduce dependency on upstream and midstream stages.

It goes beyond the scope of this report to conduct a deep analysis of why these security risks and vulnerabilities have emerged, most notably related to China's dominant position in several supply chain stages, but there are several reasons that have been highlighted in the literature.

A first factor is China's high domestic demand for clean energy technologies. China is currently the largest consumer of EV batteries, solar PV panels and wind turbines, surpassing consumption levels in other large economies. In 2022, China sold 6,8 million EVs compared to 800 000 in the United States (Yang, 2023). According to a survey from the US consulting company AlixPartners, over 50% of Chinese respondents were considering battery-electric vehicles as their next car in 2021, the highest proportion in the world and two times the global average (Yang, 2023). In 2021, China's demand for solar PV panels also accounted for 36.4% of global demand which is more than double the demand in North America (17.6%) and Europe (16.8%) (International Energy Agency, 2022c). In 2021, China had a 70% share in wind generation growth, dominating the other global players, such as the United States (14%) and Brazil (7%).[4]

A second factor is China's more affordable energy and labour costs in specific regions, which generates a latent comparative advantage in energy-intensive and labour-intensive production stages.[5] China has traditionally had a comparative advantage in labour-intensive activities due to its large population and relatively low labour costs. This has provided the country important cost advantages in the manufacturing and assembly stages of solar panel, wind turbine and EV battery supply chains. However, as China's economy has developed, some of these labour cost advantages have started to diminish. China also has a comparative advantage in energy-intensive industries, such as critical mineral processing, due to its large reserves of coal and other natural resources.

[4] https://energydigital.com/renewable-energy/china-leads-global-increase-in-wind-power-generation-patents

[5] It is important to note that energy is not generally cheap in China. Nonetheless, coal-abundant regions in China often have lower energy prices which generate localized comparative advantages.

However, China has been trying to shift its economy away from the use of coal in recent years, in order to reduce pollution and address climate change.

A third factor is China's less stringent environmental control, which can provide the country with a competitive advantage in some of the more pollutive supply chain stages such as critical mineral mining and processing. There are nonetheless indications that China has started tightening environmental regulations. A dark reality of critical mineral mining and processing is that it generally takes a tremendous amount of water and if unregulated can leave behind large quantities of toxic sludge that can generate serious environmental and health hazards. Scholarship on rare earth mining, for example, have found that producing one ton of rare earth oxide from ionic-adsorbed clays in unregulated mines can generate up to 2 000 tons of tailings and 1 000 tons of wastewater containing heavy metals (Packey & Kingsnorth, 2016). Other studies have documented similar environmental effects related to the processing lithium and cobalt (Farjana et al., 2019). Refining these critical minerals generate tailings, which if not treated and stored properly can cause water, soil, and air pollution.[6] While modern mining and refining operations can adopt methods to prevent or minimise water pollution from tailings, these require substantial investments that limit the competitiveness of firms and locations.

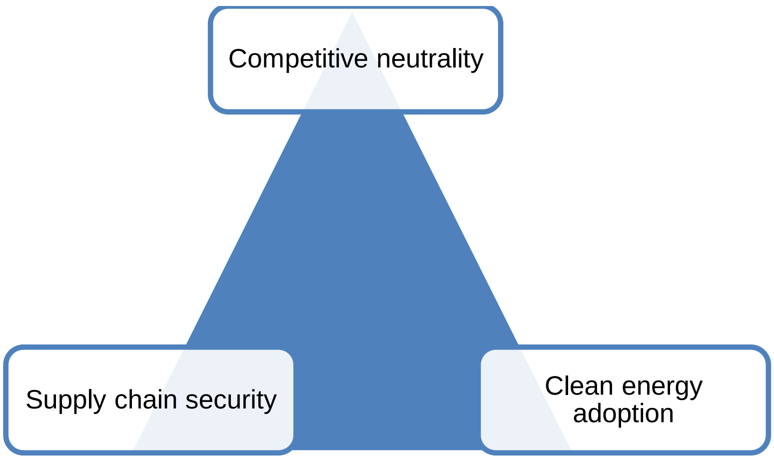
A final factor is China's supportive public policies. China began to prioritise clean energy production in the mid-2000s, as the country faced increasing pressure to address its growing air pollution problem and reduce its dependence on imported fossil fuels. Since then, the Chinese government has introduced a series of policies and incentives to support the growth of the clean energy industry, including subsidies for renewable energy projects, below-market financing, feed-in tariffs, and research and development programs. These policies have helped to drive down the cost of renewable energy technologies, led to the establishment of several pioneering domestic manufacturers, and strengthened China's dominance in several key stages of clean energy supply chains.

[6] https://www.cobaltmininglegacy.ca/backgrounder.php.

THE POLICY TRILEMMA RELATED TO CLEAN ENERGY SUPPLY CHAINS

In their quest for a robust clean energy transition, governments face several goals that are difficult to tackle together. First, they want to *support clean energy adoption* by incentivising the use of clean energy technologies. Second, they want to *secure supply chains* by adopting policies that reduce the chokepoint risks related to large geographic and market concentrations in the supply chain stages of clean energy supply chains. Third, they want to *maintain competitive neutrality* by developing a policy environment that ensures that different firm types from different countries compete on a level playing field. This section illustrates a policy trilemma between these three goals by showcasing the impact of three types of public finance policies that governments have recently adopted at different stages of clean energy supply chains (Figure 4). The section starts with the discussion of consumer tax credits for EVs that target the downstream stage of sales. It next discusses the use of below-market financing in the solar industry which targets the midstream and downstream production stages. Finally, it turns to the critical mineral strategies that several countries have recently adopted to target mining, processing and recycling.

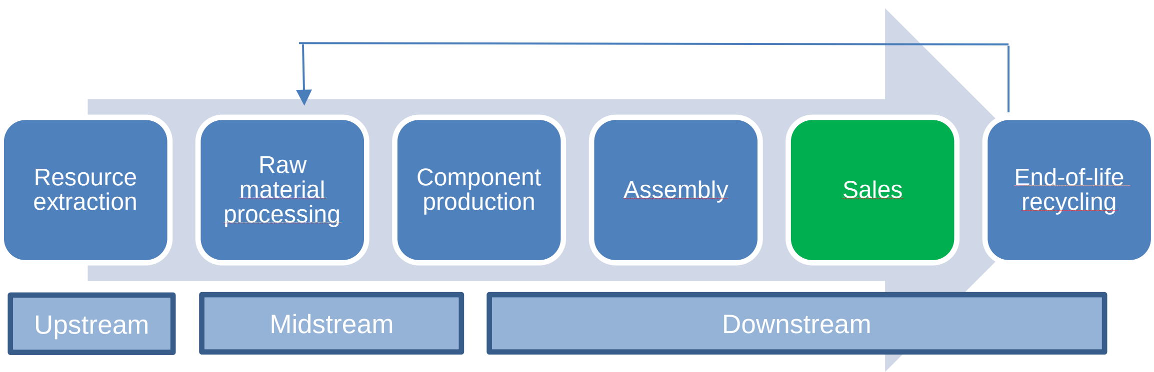
Figure 4. Clean energy supply chain policy trilemma



Case 1: Consumer tax credits for electrical vehicles

Analysis starts with an overview of one of the most important demand-pull policies that governments have used to incentivise consumers to select EVs over automobiles with internal combustion engines (Figure 5).

Figure 5. Consumer tax credits target the sales stage of EV supply chains



Most major economies have implemented consumer tax credits for electric vehicles. The idea is to subsidise buyers so that they switch over and purchase EVs instead of traditional cars with internal combustion engines. Here are a couple of prominent examples:

- China provides tax exemptions on Chinese EVs that amounts to roughly 10% of the sale price. The exemption of this levy began in 2014 to spur market growth for new energy vehicles, and it is expected to be extended beyond 2023.
- The United States provides a federal tax credit of up to USD 7 500 per EV. In 2022, the Inflation Reduction Act ended USD 7 500 consumer tax credits for purchases of electric vehicles assembled outside North America. These credits were structured so that any American buying a qualified EV could get the credit, and the more battery power in the vehicle, the bigger the credit.
- France provides a purchase incentive – eco bonus – of maximum EUR 5 000 (down from EUR 7 000 in 2020) for electrical vehicle. In addition, individuals can receive a conversion bonus if it in exchange for the new vehicle scraps an old diesel or petrol vehicle.
- Since the summer of 2016, the German government makes an environmental contribution of EUR 2 000 to the purchase of a pure electric car, combined with the same amount by the manufacturer, corresponding to a total amount of EUR 4 000. This bonus is limited to electric cars up to a value of EUR 60 000.

Clean energy adoption. The main purpose of consumer tax credits is to encourage consumers to switch from traditional cars with internal combustion engine to EVs, and evidence suggests that it works (Clinton and Steinberg, 2019). There is some debate, nonetheless, on the effectiveness of EV consumer credits as a market-supporting policy to increase the adoption of clean energy solutions. The main concern is that the subsidies are costly and not very well targeted. In her survey of the literature, Sheldon (2022) finds that the subsidy cost per additional EV is USD 30 000–35 000, which is greater than the purchase price of some EV models. Furthermore, she concludes that for the same dollar amount of total subsidies being paid out by the government, more people would have switched over to EVs if the government had increased subsidies available for lower income households and not given away as many tax credits to richer households, who would have bought the EVs anyway. Sheldon and Dua (2023) provide similar findings in China. Based on these results, Sheldon (2022) calls for better policy design that can increase the effectiveness of consumer credit programs. This includes considering how to minimise free-ridership, for example, by targeting subsidies strategically by income or vehicle replaced. More research is also needed on policy instruments that may better enable lower-income households to overcome the EV cost barrier (e.g. rebates versus tax credits, financing programmes). Given the lower mileage that EVs appear to be driven, more research is warranted on targeting electric miles rather than EV market penetration.

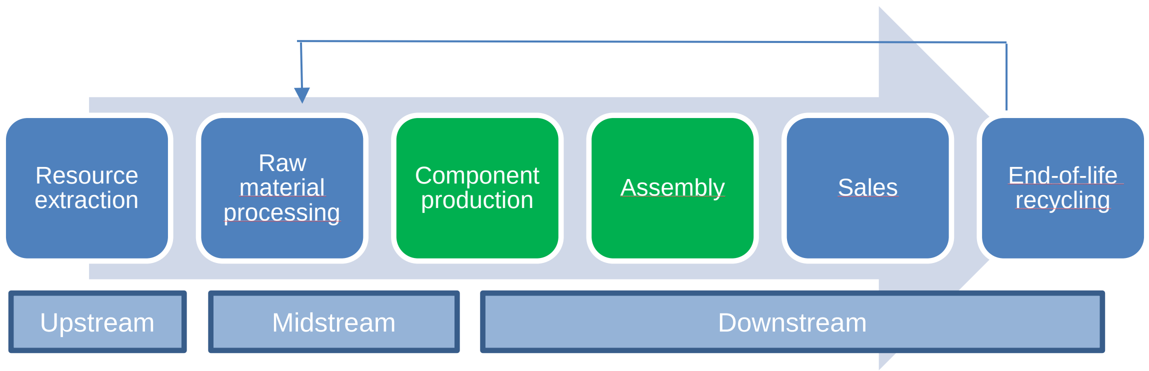
Competitive neutrality. Consumer tax credits do not generally prevent, restrict or distort competition by favouring or discriminating against EVs based on their ownership, production location or nationality. They sometimes are made conditional on the sticker price of the car or on the income-level of consumers, but this is not considered to go against the fundamental principles of competition law and policy. EV consumer tax credits therefore neither strengthen nor weaken competitive neutrality.

Secure supply chains. EV tax credits do not generally favour or discriminate against EVs based on their ownership, production location or nationality and therefore do little to address security concerns related to the high geographic and market concentration of different stages of the EV battery supply chain. A notable exception is the decision of several countries to make EV consumer tax credits conditional on domestic content provisions. This policy change illustrates the trade-off that can exist between securing supply chains and maintaining a competitively neutral market environment.

Case 2: Below-market finance in the manufacturing of solar panels

Below-market finance is a supply-side push policy that several governments have adopted to promote their firms and local production in the supply chain segments of component production and final assembly of solar PV panels. It can take the form of either below-market borrowings – where governments provide support through debt financing – or below-market equity – where governments provide equity finance on terms that are inconsistent with market principles (OECD, 2021). In both cases, below-market finance serves to lower companies' cost of capital, thus providing them with a competitive advantage in both local and global markets.

Figure 6. Below-market financing targets the component production and assembly stage of solar PV panel supply chains



A 2021 OECD report has shown that below-market borrowings (and not so much below-market equity) are a prevalent feature in the global solar PV industry. Most support identified was found to benefit industrial firms based in China, which partly reflects the market concentration discussed above but also a greater propensity for Chinese authorities to use this particular support instrument (OECD, 2021).

Secure supply chains. Some governments have used below-market financing to increase domestic production capacity for solar panels, thus supporting domestic self-reliance and boosting global competitiveness. OECD (2021) found that below-market borrowings are correlated with two features that may help explain the large geographical concentration of midstream and downstream stages in solar PV panel supply chains in China. First, below-market financing is correlated with larger investments in fixed tangible assets at the firm level, which suggests that it can help solar companies in expanding their domestic manufacturing capacity. Second, capacity increases are negatively correlated with solar-panel prices, suggesting that they can encourage significant scale economies in the industry (see also Kavlak et al., 2018; Brandt & Wang, 2019). Below-market financing appears, however, to be negatively correlated with firm productivity, suggesting that the effectiveness of this type of supply-side policy is limited.

Clean energy adoption. Below-market financing may reduce the sticker price of solar PV panels, which can be a boon for solar panel adoption. Between 2006 and 2013, Chinese state subsidies contributed to the rapid increase of China's global share of PV cell production from 14% to 60%, which went hand-in-hand with a steep drop in the global average price per watt of PV capacity. Prices have continued to fall since then, and China remains the dominant producer. A recent study by ITIF nonetheless points out that it may have come at a cost of new innovation in solar technology, with innovative firms especially outside of China being driven out of business due to the low subsidized prices in China (ITIF, 2020). This may constrain the solar PV panel industry's ability to develop new technologies, in the medium term limiting clean energy adoption.

Competitive neutrality. While there can be valid justifications for subsidies such as below-market finance, including market failures, this type of policies also risks distorting competition by providing a competitive advantage to recipients, especially if their selection is related to ownership type, production location, and nationality. It undermines the global level playing field by allowing less innovative, less efficient, or less competitive companies that receive support to crowd out other firms. And it can generate countermeasures by other countries that can further reduce the competitively neutral environment, generate tensions that can increase supply chain security concerns, and dampen clean energy adoption.

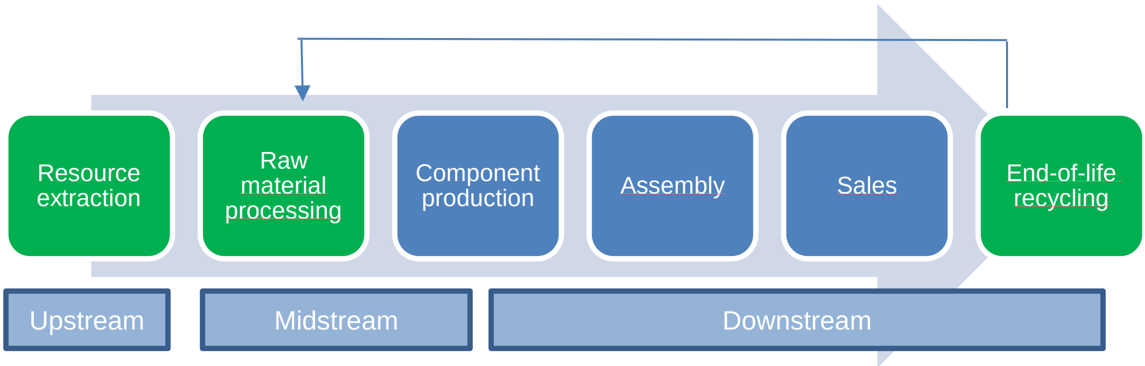
Case 3: Critical minerals strategy

Several countries with limited production capabilities in critical minerals have developed critical minerals strategies, including Canada, Australia, the United Kingdom and the European Union. These strategies generally focus on three directions of unilateral policy action (Calvino, 2022):

1. increasing domestic resource extraction and processing capabilities and diversifying supply;
2. supporting innovations that develop substitute materials for critical minerals;
3. increase the recyclability of critical minerals.

In some cases, the development of these critical minerals strategies have been coordinated across countries. G7 countries, for example, have joined forces with Australia, Finland, Korea, Norway and Sweden to establish the Minerals Security Partnership (MSP), an initiative that aims to build robust, responsible critical mineral supply chains.

Figure 7. Critical mineral strategies target the resource extraction, raw material processing, and end-of-life recycling stage of clean energy supply chains



Secure supply chain. The main aim of critical mineral strategies is to eliminate chokepoints in clean energy supply chains by strengthening the domestic capacity to extract and process minerals and metals, diversify supply chains by setting limits on the amount of minerals that can be sourced or processed from a single country, develop new clean energy technologies that are less dependent on critical minerals that have limited and concentrated supply, and increase the supply of critical minerals through end-of-life-recycling.

Competitive neutrality. The efforts to strengthen domestic capacity and diversify supply chains may distort market competition if policies provide subsidies that discriminate against firms based on ownership or nationality and aim to strengthen dominance on export markets, thus undermining the level playing field.

Clean energy adoption. The impact of critical minerals strategies on clean energy adoption is ambiguous. On the one hand, investment in production capacity may dampen the prices of clean energy products by stabilizing or lowering the price of critical minerals. On the other hand, reductions in competitive neutrality may generate tensions that reduce the stability and security of clean energy supply chains.

CONCLUSIONS AND POLICY IMPLICATIONS

This report has unveiled evidence of substantial geographical and market concentration in clean energy supply chains. It points out that these high geographical concentrations may generate chokepoints risks where natural disasters or policy decisions in a specific region/country reverberate through clean energy supply chains and negatively affect the efforts towards a clean energy transition. High market concentrations can generate similar chokepoints related to firm-specific effects.

The report further highlights that policymakers face a policy trilemma in their efforts to avoid such chokepoints where it is difficult to develop policies that simultaneously support secure supply chains, promote clean energy adoption, and maintain competitive neutrality. First, governments need to consider the trade-offs between efficiency and resilience in their policy choices where efforts to diversify the sourcing of supply chain stages with high chokepoint risks may generate important cost increases that disincentivise clean energy adoption. Second, governments need to take into account the trade-off between competitive neutrality and resilience where policies to increase domestic production and diversify supply chains often lead to discriminatory policies that are not in compliance with existing international rules and practices. This may lead to international tensions and retaliation policies that can further endanger the security of clean energy supply chains and can generate subsidy races.

Avoiding conflict and encouraging collaboration between G7 countries as well as with non-G7 countries are important elements that should be centre of mind in the development of public finance policies aimed to address this policy trilemma. Strategic co-operation between countries can go far in reducing chokepoint risks and secure supply chains without necessarily impeding competitive neutrality. These joint strategies may include efforts to facilitate trade in clean energy supply chains, joint measures to promote R&D and end-of-life-recycling, and joint efforts to combat unfair trade practices. They may also include multilateral engagements to support resource- rich countries to play bigger roles in the middle and downstream of clean energy supply chains. And they can include agreements to promote social and environmental standards in clean energy supply chains, making them both resilient and inclusive. Examples of such initiatives include the Minerals Security Partnership (MSP) under which G7 countries cooperate with several other Western nations to build robust, responsible critical mineral supply chains.

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