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Trade-offs of wind power production: A study on the environmental implications of raw materials mining in the life cycle of wind turbines

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A R T I C L E I N F O

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ABSTRACT

The energy demand in Sweden is increasing due to the growing electrification, and to meet this need, the generation must be expanded. Wind power generation is a very attractive renewable power production alternative for Sweden because of the favorable weather conditions.

Research looks at how much wind energy may be deemed sustainable. Increased energy demand puts pressure on the government and industry to build more wind farms and, as a result, produce more wind turbines. Raw materials are necessary for wind turbines to provide a secure transition to green energy technologies. To meet these demands, the materials from various countries should efficiently contribute towards the Sustainable Development Goals (SDGs). This paper gathers information about raw resources from diverse nations worldwide. All materials are mapped to the country where they are produced using social science criteria. A few nations are chosen based on a sample approach for further analysis, and the implications of mining operations are investigated. Finally, the direct and indirect effects of the SDGs are considered.

Based on the data gathered, recommendations and considerations are given to avoid or mitigate the repercussions of raw materials mining and make wind power generation more socially and environmentally sustainable.

1. Introduction

Renewable energy sources are fundamental for sustainable energy transitions, and their deployment is a key factor in taking action against climate change. The Paris Agreement (2015) set up as the primary long-term goal to constrain the rise in mean global temperature to 1.5 °C above pre-industrial levels to reduce emissions and limit the effects of climate change. To achieve this, it is necessary that the CO_2 emissions will reach net zero by 2050. It is, therefore, essential to create a more sustainable lifestyle that involves the accomplishment of the 17 Sustainable Development Goals (SDGs) established in 2015. Sustainable development can be seen from different perspectives, and the idea is to create partnerships in several areas for faster growth between developed and developing countries. Several goals handle the possible usage of renewable energy and sources that could help diminish emissions compared to the corresponding fossil fuel technologies.

In January 2018, Sweden introduced legislation for the country's long-term goal to reach net zero emissions by 2045, five years ahead of the previously mentioned global goal. The Swedish Climate Act includes specific goals to reach this necessary objective. Sweden has also set up the goal to reach 100% usage of electricity from renewable sources by 2040 (IRENA, 2020). The main renewable source in Sweden is hydropower; however, wind power has been increasing rapidly in the last decades. Wind power is one of the most promising renewable sources that has grown in the past few years. Wind power accounted for 23% of the total global renewable shares of power generation in 2021 (IEA, 2022). The global installed capacity from wind power in 2022 was 906 GW, which accounted for a 9% increase from the installed capacity in 2021. Sweden produced a total of 0.5 TWh in 2000 from wind power generation, reaching 27.4 TWh in 2021 (Energimyndigheten, 2022). This fast-growing pace could be even further exploited given the wind exposure that Sweden is subjected to.

Wind power is a promising source of green energy. Wind turbines do not have major environmental impacts during operation; however, it has been shown that the principal emissions during their lifetime come from the manufacture and installation processes (Pehnt, 2006). For this reason, it is fundamental to analyze the various environmental impacts that energy sources can have during the different processes of their lifetimes. Consequently, reasonable investments can be made in planning and developing a specific energy system. One of the approaches used for considering the environmental impacts of an energy system is

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the life cycle assessment (LCA). Adopting the LCA approach can help improve the system's sustainability from the project's early stages. It is used to evaluate a system's emissions and possible impacts, from extracting its raw materials to the end of its life when the technology is decommissioned.

During the past years, technologies have been developed to improve the quality of life and society. However, when developing new technologies for a sustainable society, researchers typically do not include the consequences of constructing the technologies because they must focus on their technical mission. An example is the energy system design. According to the Swedish Wind Energy Association, wind generation will increase from 30 TWh to 120 TWh in 2040 (Swedish Wind Energy Association, 2021). The technical aspects of today's energy system design are well-developed; furthermore, social sciences have thoroughly studied issues such as energy policies and the impact of energy systems on human well-being. Due to a need for more communication between the scientific fields, sustainable development is interpreted narrowly. The technical solutions made from the scientific fields are on a semi-informed basis since the consequences of sustainable development for the environment and society are not considered.

Research reveals that yearly trash from installed wind turbines would increase at a gradual rate of roughly 12% per year until around 2026. Afterwards, the increase of trash will be at a rate of 41% per year until 2034. Annual waste quantities are expected to reach 237,600 tonnes of steel and iron (16% of already recycled amounts), 2300 tonnes of aluminum (4%), 3300 tonnes of copper (5%), 343 tonnes of electronics (1%), and 28,100 tonnes of blade material by then (Andersen, 2015). Moreover, wind turbine blades cannot be recycled at the end of their lifespan (Martin, 2020).

This paper combines energy system planning and social and environmental issues into the technical design and an assessment of ethics and impact on communities locally. The work focuses on the impacts of wind power generation on increased energy demand. It explains how wind power is produced and the requirements to develop a wind turbine. Moreover, studies are done on how the raw materials needed to construct a wind turbine affect the environment and society.

The research area is critical to a future climate-neutral and socially fair world. Also, a focus on human well-being and environmental preservation are prioritized in the wind turbines' design and evaluated based on their impact on all Sustainable Development Goals (SDG). Due to the growing demand for electricity and renewable energy sources and to achieve such a vast target, there is a need for coordination of knowledge and information to understand the implications of factors required to generate wind power.

The influential parameters should be examined, including the required materials, how and where they are bought and mined, the material's environmental and societal impact, and the interrelation between sourcing countries. This results in making more impartial and trustworthy decisions to reach the UN's Sustainable Development Goals, considering the life-cycle assessment.

The work aims to analyze and evaluate how renewable and sustainable the existing wind power generation is by considering a wind turbine's ecological and social footprint. The goal is achieved by identifying the components necessary to create a wind turbine, exploring where their raw materials are designed and mined, and how the extraction of the raw materials impacts the environment and society. The ethics behind the affected communities compared to the UN SDG are also discussed.

The paper has the following contributions:

- Identify the components necessary to develop a wind turbine and investigate the extracting and mining source of the corresponding raw materials.
- Determine how mining and extraction activities are unethical regarding human welfare.
- Analyze how the extraction of the raw materials affects the environment.
- Inspect the ecological and societal footprint of wind power.

The paper is structured in the following way. Section 2 introduces some related work in the field of life cycle assessment of wind farms. In Section 3, the methodology of the work is outlined. Section 4 gives an overview of the data utilized, focusing on the materials used in wind turbines. The results and consequent discussion are presented in Section 5. Finally, Section 6 concludes our findings and describes the future steps in the research.

2. Related work

The renewable energy transition refers to the shift from fossil-based sources, including oil, coal, and natural gas, to renewable energy sources, comprising wind and solar. Different studies analyze this transition, considering several aspects of carbon emissions. In Wang et al. (2023), the authors establish a model to analyze the carbon emissions in the renewable energy transition and the influence of metallic minerals on the emissions. The results show that metallic minerals promote CO_2 emissions. The authors in Chen et al. (2023) focus on the effects of the renewable energy transition on metal minerals consumption. The results indicate that critical metals are more in demand for consumption as we transition to more renewable energy sources. Solutions to protect these metal minerals include strategies for critical metal reserves, replacement of materials, and their recycling. A risk assessment framework is presented in Schischke et al. (2023), analyzing the sustainable energy transition and the demand for scarce resources applied to the German energy transition (Energiewende). Cobalt, used for energy storage, is the highest in demand; however, it has a high probability of scarcity, which could be problematic. In the paper (Shammugam et al., 2019), the authors focus on wind energy development in Germany. The metallic raw materials required are assessed, and the study concludes that copper and dysprosium are the most critical materials. The study conducted in Verma et al. (2022a) determines the amount of raw materials, rare earth elements, and critical metals needed to manufacture wind turbines that, in the future, will account for full wind energy production in India. An LCA is carried out in Shenbagaraman and Gnanavel (2023) on an offshore wind farm in India to evaluate the different life cycle stages of the wind turbines. The manufacturing stage has one of the major environmental impacts; moreover, the study highlights the human toxicity affecting adults by styrene and glass fibers. The authors in Li et al. (2022) focus on offshore wind energy worldwide and the type of materials required for this energy development. More materials will be required in the future as more MW turbines will be installed offshore. The priority of reducing the demand for materials is to extend the wind turbines' lifetime, improve their materials utilization, and introduce and develop novel technologies.

A few examples of LCA applied to European wind power projects are summarized here. A comparison of the energy use of onshore and offshore wind farms is made by Schleisner (2000), while the environmental impact of a wind turbine from the extraction of its raw material to the end of its life is described by Elsam Engineering A/S (2004). Pehnt et al. (2008) and Weinzettel et al. (2009) focus on the environmental impact and CO_2 emissions of offshore wind turbines, respectively. Focus on a 2 MW turbine was given by E. Martínez et al. in Martínez et al. (2009b,a) and Martínez et al. (2010), while Guezuraga et al. (2012) compare two different 2 MW wind turbines, analyzing environmental impacts. Another comparison of two 2 MW wind turbines is made by Haapala and Prempreeda (2014) in the US context this time. Several life cycle assessments have been conducted in the Americas, Europe, and Asia. A more recent LCA in India is outlined by S. Verma et al. in Verma et al. (2022b).

Tveten (2009) propose an LCA for offshore wind farms in Scandinavia considering different scenarios.

LCA can lead to several perspectives and results of the desired analysis. It is used to understand a specific technology's effects on the environment, but these results can be read from different viewpoints. A review assessing the existing publications in resource assessment of complete energy systems is presented in Yavor et al. (2021). Several gaps are identified in the study, including the lack of publications that focus on complete renewable energy systems. The scope is often unclear, as the assessments focus on various heterogeneous sub-systems with different applications.

3. Methodology

The paper is intended as a literature study. The data for the analysis is collected from the technical publication obtained by the literature research. The study focuses on how the manufacturing of wind power plants is carried out, the type of materials needed in a wind turbine, the materials sources, and the repercussions of the material production. The information collected is then compared using the Sustainable Development Goals.

Employing more wind power leads to a decrease in greenhouse gas emissions to achieve environmental goals. Knowing a wind turbine's environmental and societal impact is crucial before it is fully installed to generate clean energy. To address these issues, researchers gathered and analyzed data on the production and trafficking of minerals used in wind turbines and the consequent social and environmental repercussions of mining them, using a variety of research approaches and sources (Kiezebrink et al., 2018).

The assessment criteria developed to compare the technology are based on four of the SDGs:

- Good Health and Well-being (SDG 3)
- Climate Action (SDG 13)
- Life Below Water (SDG 14)
- Life on Land (SDG 15)

The paper mainly covers the direct negative impacts on the SDGs listed above. The information available for the countries included in the study are the environmental impact, violations of mining laws, and violations of labor rights.

4. Data

4.1. Materials used in a wind turbine

Increased dependence on wind energy to meet established renewable energy production objectives raises the demand for the minerals required to manufacture wind turbines. To enhance wind capacity, it is vital to pay attention to the wind energy supply chain utilized in wind turbines, which usually has negative consequences on human rights for people living near mines and can harm the surrounding environment (Kiezebrink et al., 2018).

The materials used in the manufacturing of wind turbines are aluminum, boron, chromium, cobalt, copper, iron, manganese, molybdenum, nickel, rare earth elements (praseodymium, neodymium, terbium, and dysprosium) (Commission et al., 2016), and zinc (Group, 2017).

Fig. 1 shows the raw materials used corresponding to the wind turbine components. The information was retrieved from literature (Kiezebrink et al., 2018). Table 1 shows the material requirements in t/GW for different wind turbines; in particular, the direct drive electrically excited synchronous generator (DD-EESG), the direct drive permanent magnet synchronous generator (DD-PMSG), the gearbox permanent magnet synchronous generator (GB-PMSG), and the gearbox double-fed induction generator (GB-DFIG). The synchronous generators with permanent magnets (PM) have increased in demand, and their dependence on rare earth elements could lead to major costs that could cause disruptions (Shammugam et al., 2019). In Table 1, we can observe that the DD-PMSG turbine has the largest material usage for the four rare earth elements, i.e., dysprosium, neodymium, praseodymium, and terbium. The data is collected from literature (Carrara et al., 2020). From Table 1, we can notice that cast iron is the most used material in all the four turbines considered in this study. Steel still constitutes the biggest amount of a wind turbine (71%–79%), followed by cast iron (5%–17%) (Verma et al., 2022a). In Shammugam et al. (2019), the authors estimated that the consumption of iron, steel, and aluminum is not expected to exceed 6% of current demand. In their study, the authors of Kasner (2022) concluded that materials like steel, concrete, copper, aluminum, and cast iron, which can be found in large quantities in wind turbines, can be more efficiently employed for enhancing and extending wind farms' lifetimes rather than recommissioning to a wind farm with the same power.

Table 1
Material usage estimates in t/GW for different wind turbines (Carrara et al., 2020).

Material	DD-EESG	DD-PMSG	GB-PMSG	GB-DFIG
Aluminum (Al)	700	500	1600	1400
Boron (B)	0	6	1	0
Chromium (Cr)	525	525	580	470
Cobalt (Co)	N/A	N/A	N/A	N/A
Copper (Cu)	5000	3 000	950	1400
Dysprosium (Dy)	6	17	6	2
Iron (cast) (Fe)	20 100	20 100	20 800	18 000
Manganese (Mn)	790	790	800	780
Molybdenum (Mo)	109	109	119	99
Neodymium (Nd)	28	180	51	12
Nickel (Ni)	340	240	440	430
Praseodymium (Pr)	9	35	4	0
Terbium (Tb)	1	7	1	0
Zinc (Zn)	5500	5500	5500	5500

4.2. Producers of raw materials

The top manufacturers of the aforementioned raw materials are depicted in Fig. 2. Some mineral resources are extremely concentrated, with one nation dominating the production and export of a particular metal; for example, China's rare earth minerals, Turkey's boron, and South Africa's chromium and manganese. Mineral deposits, on the other hand, are usually found in many nations. It should be noted that some of the minerals' principal place of origin might change swiftly and unpredictably owing to market dynamics, shifting prices, and political (in)stability (Carrara et al., 2020).

The locations where minerals are mined to manufacture wind turbines are dispersed over the globe, as seen in Fig. 2. Some minerals, such as aluminum, iron, and nickel, are primarily produced in highly industrialized countries like Australia and Canada. However, poor and middle-income countries like Brazil, Chile, China, Gabon, India, Indonesia, Kazakhstan, Madagascar, Myanmar, Peru, Russia, South Africa, Turkey, the Democratic Republic of Congo (DRC), and the Philippines mine a substantial share of the minerals needed for wind turbines (Carrara et al., 2020).

4.3. Sampling

Fig. 2 shows the wind turbines' materials defined by the countries' combined total production of the materials and by different social parameters. However, the listed materials are the less common, as researchers want to raise awareness of the more unknown elements. Indeed, materials like cement and iron are not inserted in the total plotted production. The rare earth metals are combined due to the difficulties of finding the total production of the individual elements. Therefore, the materials taken into account are aluminum, boron, chromium, cobalt, copper, manganese, molybdenum, zinc, and rare earth metals, including praseodymium, neodymium, terbium, and dysprosium.

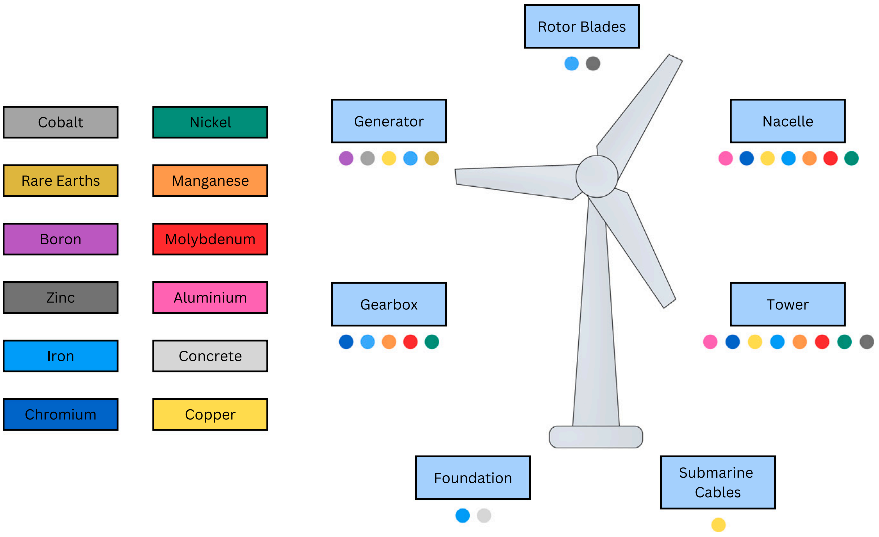

Fig. 1. Raw materials used in wind turbines.

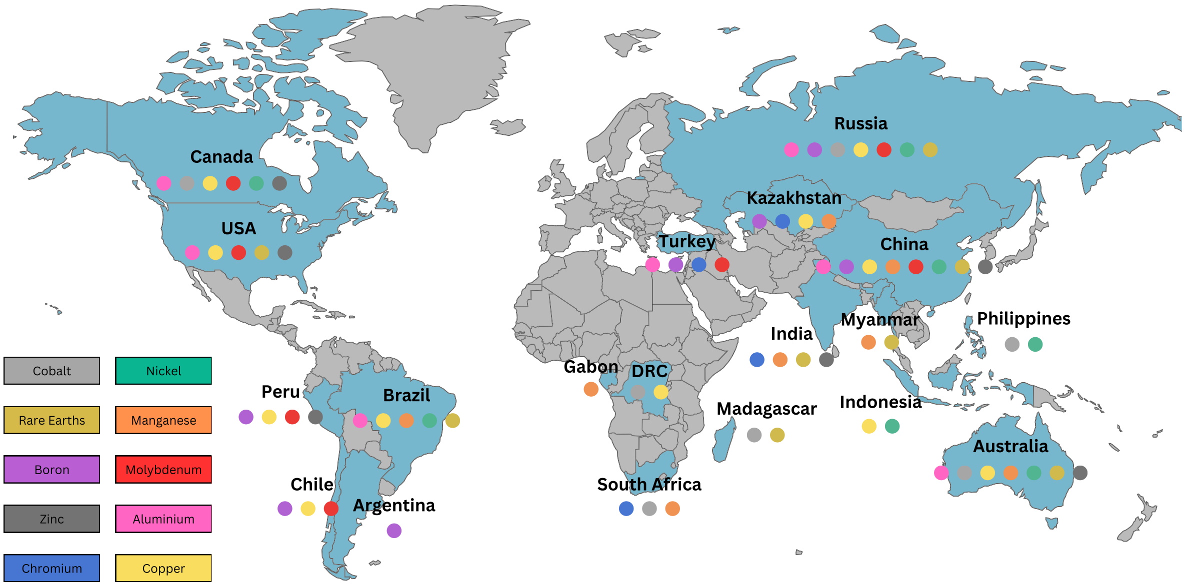

Fig. 2. The top-producers of minerals and metals used in wind turbines (Carrara et al., 2020).

Some social parameters are gathered and plotted based on the materials mainly produced by the nations. For example, Sweden produces very little, so it has been excluded from this analysis. The social parameters taken into consideration are rankings based on the human development index (United Nations Development Programme, 2019), social support, healthy life expectancy, and the freedom to make life choices (Helliwell et al., 2021), which are plotted in Figs. 3, 4, 5, and 6, respectively. The four social parameters have the following definitions:

- Human development index: “It measures the capability to live a long and healthy life, to acquire knowledge and to earn income for a basic standard of living” (United Nations Development Programme, 2019)
- Social support: it represents the average of binary responses, either 0 or 1, to the following question in the Gallup World Poll (GWP) nationally: “If you were in trouble, do you have relatives or friends you can count on to help you whenever you need them, or not?” (Helliwell et al., 2019).
- Healthy life expectancy: the data is taken from the World Health Organization (WHO) Global Health Observatory repository (Helliwell et al., 2019).
- Freedom to make life choices: it represents the average of binary responses, either 0 or 1, to the following question in the Gallup World Poll (GWP) nationally: “Are you satisfied or dissatisfied with your freedom to choose what you do with your life?” (Helliwell et al., 2019).

The plots show that Australia, South Africa, China, and Turkey are the leading materials producers. However, South Africa, China, and Turkey have the lowest scores in all assessment criteria. The three countries are then analyzed in correspondence to the four selected SDGs, namely SDG 3 on “Good Health and Well-being”, SDG 13 on “Climate Action”, SDG 14 on “Life Below Water”, and SDG 15 on “Life on Land”.

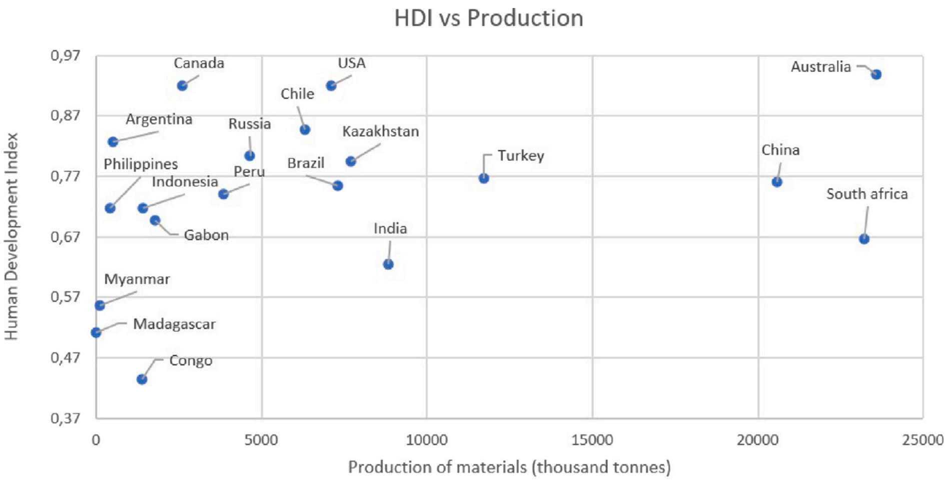

Fig. 3. A plot of the countries' rank on the human development index and the total production of materials used in a wind turbine.

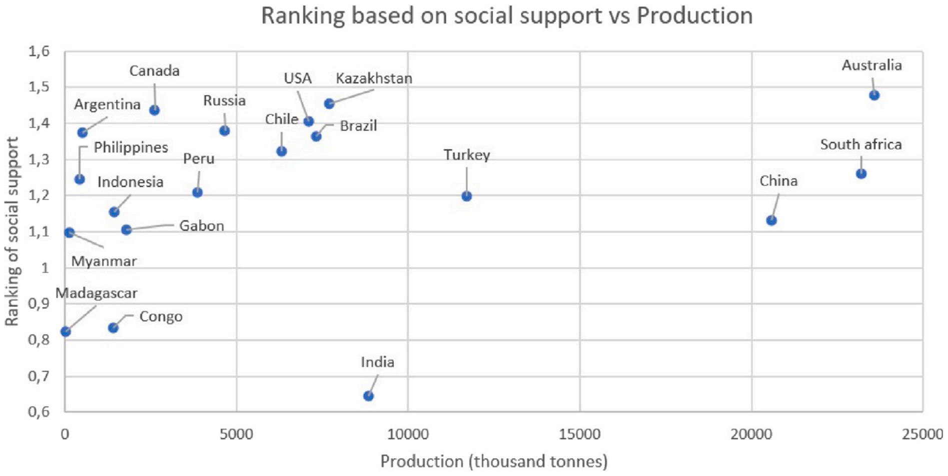

Fig. 4. A plot of the countries' rank based on the social support and the total production of materials used in a wind turbine.

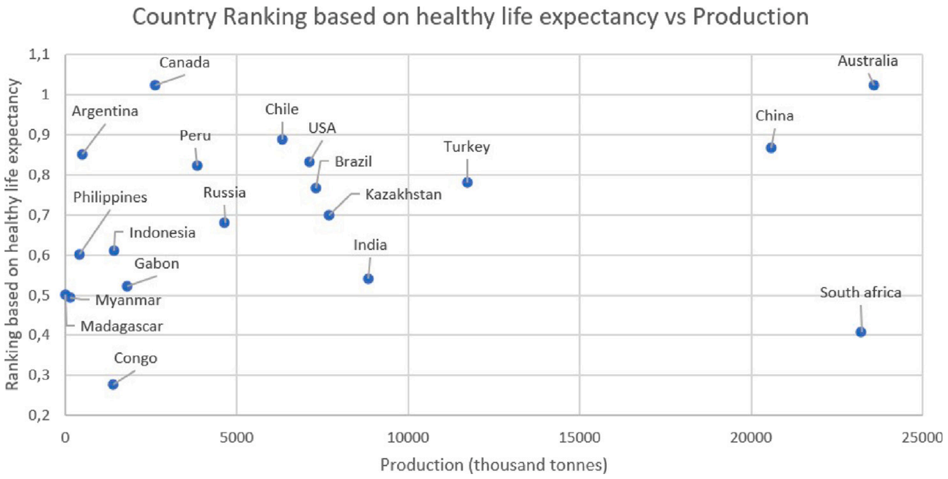

Fig. 5. A plot of the countries' rank based on the healthy life expectancy and the total production of materials used in a wind turbine.

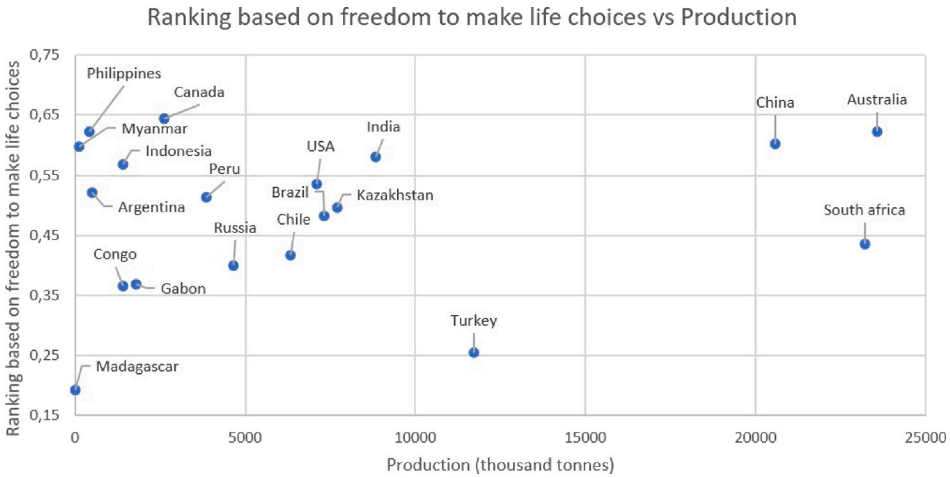

Fig. 6. A plot of the countries' rank based on the freedom to make life choices and the total production of materials used in a wind turbine.

4.4. Materials

The materials we are investigating for producing wind turbines are briefly introduced here.

Aluminum (Al)

One of the materials used in wind turbine production is aluminum, and China is one of the largest producers. When aluminum is extracted, a waste product is created. The waste product is red mud, a mix of undissolved alumina, iron oxide, silicon oxide, titanium oxide, and other metals in smaller quantities. The mining of aluminum emits CO_2 emissions. The global average of CO_2 emissions for both mined aluminum and recycled aluminum is 11.5 tonnes of CO_2 per tonne of aluminum (Clemence, 2019).

Boron (B)

Typically, boron is extracted in open-pit mines by drilling, blasting, crushing, and hauling all activities fueled by petrochemicals. The refining process then uses a significant amount of water. Finally, the waste product is deposited in artificial ponds where further refining is done before the water is discharged into the local watershed (American, 2009).

Chromium (Cr)

Chromium mining takes place mostly in South Africa. Usually, the mines are situated in rural areas where people live off the land with their livestock. Mining companies, by law, are required to make binding commitments for projects that will benefit a community affected by mining, but the communities are rarely consulted. Instead, they get a job in the mines as compensation for the land that is taken away (Schwarz and Mokgalaka, 2020).

Cobalt (Co)

When mining cobalt, particles are emitted. These include radioactive particles, cancer-causing particles, and more health-critical particles (Farjana et al., 2019a).

Copper (Cu)

Copper is a common extracted material, as it is used in most products nowadays. One example of the usage of copper is in electrical cables. However, the extraction of copper often requires a lot of land and can create several environmental problems. The CO_2 emissions of copper equal 2.4 kg of CO_2 per kg of copper (Islam et al., 2020).

Dysprosium (Dy)

Dysprosium is a rare earth metal, and only about 100 tonnes are produced worldwide each year, with 99% of the total production coming from China, the Bayan Obo district in Inner Mongolia. The mines of Bayan Obo are the largest deposits of rare earth metals yet found and are responsible for 45% of global rare earth metal production. Approximately 75 cubic meters of acid wastewater, 12,000 cubic meters of waste gas, and approximately one tonne of radioactive waste are released per tonne of mined rare earth metals in Bayan Obo (Zapp et al., 2018).

Manganese (Mn)

Manganese is an essential material for producing iron and steel and is very common on earth. Manganese is also used for other purposes. For example, it is a catalyst to decolorize and make violet-colored glass. Moreover, the different compounds of manganese are used to create dry cells and batteries. However, manganese needs to be refined, and this process creates waste emissions both in the sea and in the atmosphere (Farjana et al., 2019b). Manganese mining emits 6.0 tonnes of CO_2 per tonne mined manganese (Westfall et al., 2016).

Molybdenum (Mo)

Molybdenum is only found in various oxidation states in minerals and does not occur naturally as a free metal on Earth. In 2011, China, the United States, Chile, Peru, and Mexico were the primary molybdenum producers. The overall deposits are believed to be 10 million tonnes, with the majority concentrated in China, Chile, and the United States (Outteridge et al., 2020). Molybdenum mining emits 5.7 tonnes CO_2 per mined tonne material (Politis et al., 2017).

Neodymium (Nd)

To obtain neodymium, uranium and thorium are combined. Following their usage, these radioactive elements and a plethora of other harmful substances are discharged into the nearby environment (A publication of the Green Court of Auditors, 2013). It has been estimated in an article by the Digital Journal that for every ton of neodymium produced, 340,000 to 420,000 cubic feet of hazardous fumes, 2600 cubic feet of acidic water, and one tonne of radioactive waste are created (Graham, 2015).

Neodymium consumption has rapidly increased in China over the past few years from producing electric vehicles and wind turbines (Geng et al., 2021). Regarding wind power generation, direct-drive wind turbines have higher efficiency and reliability and cheaper maintenance costs than typically geared wind turbines (Marx, 2018). However, they require a considerable number of neodymium permanent magnets (NdFeB). Direct-drive wind turbines have a market share of

Table 2
Estimation of the range of materials usage in t/GW and the corresponding location in wind turbines (Carrara et al., 2020).

Material	Turbine location	Usage
Aluminum (Al)	Nacelle, Tower	500–1600
Boron (B)	Generator	0–6
Chromium (Cr)	Generator, Nacelle, Tower	470–580
Cobalt (Co)	Generator	N/A
Copper (Cu)	Generator, Nacelle, Tower, Submarine Cables	950–5000
Dysprosium (Dy)	Generator	2–17
Iron (cast) (Fe)	Foundation, Gearbox, Generator, Nacelle, Rotor Blades, Tower	18 000–20 800
Manganese (Mn)	Gearbox, Nacelle, Tower	780–800
Molybdenum (Mo)	Gearbox, Nacelle, Tower	99–119
Neodymium (Nd)	Generator	12–180
Nickel (Ni)	Gearbox, Nacelle, Tower	240–440
Praseodymium (Pr)	Generator	0–35
Terbium (Tb)	Generator	0–7
Zinc (Zn)	Rotor Blades, Tower	5500

around 20%, which will grow quickly. In such circumstances, the future demand for neodymium for electric vehicles and wind turbines will be significant (Geng et al., 2021).

Praseodymium (Pr)

Praseodymium is one of the rare earth metals used in wind turbines. The generator mostly uses it as a permanent magnet (Alves Dias et al., 2020). Only two forms of ore, monazite and bastnasite, contain praseodymium, which may be found in China, the United States, Brazil, India, Sri Lanka, and Australia. The annual production of this element is at 2500 mt, with 2 million tonnes of reserves globally (Emsley, 2011; Stwertka, 2002).

Terbium (Tb)

Terbium is also a rare earth metal used in wind turbines. Terbium is not a very uncommon metal, but it is rare in the sense of supply and demand. It has become even more difficult to find after the discovery of being a critical factor of renewable energy products (Bradsher, 2009).

Zinc (Zn)

Soil is easily polluted by zinc mining and smelting activities. Previous research has demonstrated that soils and plants adjacent to mining areas are heavily polluted with lead (Pb), cadmium (Cd), and, to a lesser extent, zinc (Zn) and copper (Cu). Concentrations of heavy metals in polluted soils mostly exceed soil quality criteria III according to national standards (GB 19618-1995 China), and those polluted lands are no longer appropriate for agricultural production (Zhang et al., 2012). Zinc mining emits 0.58 tonne of CO_2 into the environment per mined tonne of zinc (Van Genderen et al., 2016).

Table 2 presents a summary of the materials with their corresponding location in the wind turbine and their range of usage for the four selected turbines from Section 4.1, i.e., DD-EESG, DD-PMSG, GB-PMSG, and GB-DFIG.

5. Results and discussion

The countries producing the majority of the materials used to construct wind turbines are mainly involved in mining, which exploits sustainable development goals. Some activities result in serious human health risks and environmental impacts; for example, the working conditions to get chromium in the mines of South Africa. In particular, distant and inaccessible small mines and smelters may be associated with serious and undocumented pollution (Zhang et al., 2012). The effects of element mining on sustainable development goals can be stated quantitatively and non-quantitatively. Several factors can be defined as quantitative data, i.e., measurable data, such as the emission of CO_2, the discharge of radioactive wastes in the water, air, or land. However, data on child labor, unethical behaviors, and other issues can be described as non-quantitative implications for the SDGs. Furthermore, the impacts on SDGs can be categorized as (Chalmers, 2019):

- Direct positive impact
- Indirect positive impact
- No impact
- Indirect negative impact
- Direct negative impact
- More knowledge needed

In our work, we mostly focus on the direct negative impacts. However, numerous indirect negative impacts on SDGs are also briefly introduced. Based on the relevance of the information extracted, the SDGs directly impacted and discussed are SDG 3, on “Good Health and Well-being”, SDG 13, on “Climate Action”, SDG 14, on “Life Below Water”, and SDG 15, on “Life on Land”. The negative indirect impacts are analyzed on each SDG separately. After identifying the lowest scoring countries in Section 4.2, we are now relating the negative indirect impacts of materials mining for these countries in accordance with the four SDGs we are considering. The analysis focuses on the following parts:

- The materials that directly negatively impact the SDGs are identified.
- Reports and papers that address the negative direct effects are reported.
- Examples of mines and deposits from the countries identified in Section 4.2 are taken into consideration.

5.1. SDG 3: Good health and well-being

Many reports have documented the direct and indirect health effects of multiple heavy metal pollutants in China. Lead and cadmium are the prominent human health hazards of zinc mining. Exposure to these materials leads to high blood lead levels in children as well as malacosteon, kidney damage, and relatively complex cancers (Zhang et al., 2012).

The mines of Bayan Obo are the largest deposits of rare earth metals yet found and are responsible for 45% of global rare earth metal production. In the outskirts of Baotou, China’s Inner Mongolia autonomous province, what could look like a vast lake with multiple streams from the air is a murky stretch of water where neither fish nor algae can grow on the ground. Nearby, factories dump chemicals-laden water into this vast 10-square-kilometer tailings pond, which generates the world’s 17 most sought-after minerals, the rare earth metals. If ingested, this hazardous water causes pancreatic and lung cancer, as well as leukemia (Bontron, 2012).

The work conditions in South Africa’s Platinum Group Metals (PGM) mines result in environmental pollution and health concerns. Moreover, some African mines release toxic waste into the water streams, resulting in polluted drinking water for nearby villages and animals. As a result, for nearby villages, their only option for fresh water is to buy bottled water (Schwarz and Mokgalaka, 2020).

Further, according to some estimations, China illegally mined 12.3–17.0 kt of neodymium resources in 2016, accounting for 40.5–41.4% of China’s neodymium market. From the standpoint of MFA, this study verifies the earlier estimation of illicit rare earth elements minerals (Geng et al., 2021).

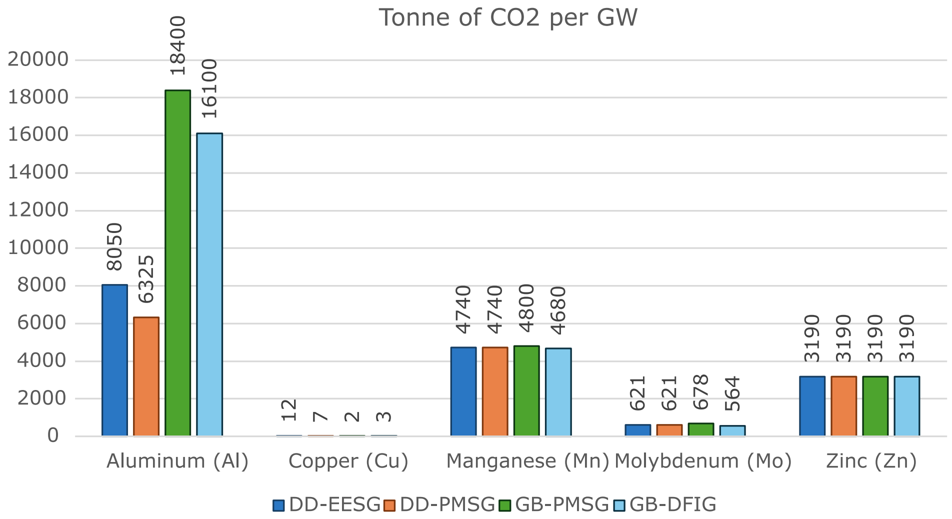

Fig. 7. A comparison between the different materials and their total CO_2 emission for one DD-EESG, one DD-PMSG, one GB-PMSG, an one GB-DFIG wind turbines.

5.2. SDG 13: Climate action

Zinc mining and smelting activities may quickly contaminate the soil. Cadmium and, to a lesser degree, zinc, and copper extensively contaminate soils and plants around mining regions. Heavy metal concentrations in contaminated soils often exceed soil quality criterion III, according to national regulations (GB 19618-1995 China), and the lands become no longer suitable for agricultural development (Zhang et al., 2012).

In April 2014, the researchers collected soil, house dust, and river water samples in the town of Jinding, near the Myanmar border, and sent them to an independent laboratory for analysis. The findings indicated cadmium concentrations up to 142 times the national health threshold and lead concentrations up to eight times the norm, indicating that the soil is unsafe for food production (Chan, 2015).

Another mining production that affects the climate is the mining of copper. The production process of copper damages the environment because of the CO_2 emissions. Its CO_2 emissions equal 2.4 kg of CO_2 per kg of copper (Islam et al., 2020). Not only copper but also manganese causes CO_2 emissions; refining this material creates 6.0 kg of CO_2 per kg of manganese (Westfall et al., 2016).

5.2.1. CO_2 Emissions

Wind power generation releases less CO_2 emissions compared to, for example, fossil fuel generation. Certainly, when it comes to wind energy as a finished product, the emissions are fewer than those of other power sources. However, building and installing wind turbines necessitates masses of materials, the mining of which is energy-demanding and contributes to the emission of large amounts of CO_2 (Helman, 2021).

For example, we consider four different wind turbines: one direct drive electrically excited synchronous generator (DD-EESG), one direct drive permanent magnet synchronous generator (DD-PMSG), one gearbox permanent magnet synchronous generator (GB-PMSG), and one gearbox double-fed induction generator (GB-DFIG). Fig. 7 shows the carbon footprint at mining various essential elements of the four selected wind turbines. The resulting plot follows the amount of each material needed as reported in Table 1 and the total CO_2 emission released when mining the materials as presented in Section 4.4.

Fig. 7 shows that aluminum, manganese, and zinc are the top three materials for CO_2 emissions in all four wind turbines. Considering the total CO_2 emissions for each material reported in Section 4.4, aluminum is the element with the most emissions. This is particularly valid for wind turbines with gearboxes as a type of generator, namely GB-PMSG and GB-DFIG. Also, zinc has a large CO_2 emissions; however, its presence is higher in these types of wind turbines, and its total average global emissions are lower than aluminum and manganese.

CO_2 can last for thousands of years in the atmosphere; it contributes to respiratory problems caused by smog, air pollution, and climate change by trapping heat. Other implications of climate change produced by CO_2 emissions include extreme weather, food supply shortages, and increasing wildfires. The weather patterns we are accustomed to will shift; some species will vanish, and others will relocate or expand (Nunez, 2019).

5.3. SDG 14: Life below water

Aluminum is one of the major contributors to water contamination, owing to its vast natural occurrence and industrial use. Aluminum is hazardous to creatures like fish and invertebrates in the aquatic environment that breathe via their gills because it causes them to lose their osmoregulatory function (Hegde, 2019).

Pollution from wastewater related to mining (ore-dressing) and smelting poses a significant threat to aquatic bodies around zinc mining companies. According to research, heavy metal concentrations in contaminated water bodies typically exceed water quality threshold V set by national regulations (GB 3838-2002 China). Zinc and cadmium are the primary contaminants. Most pollutants are deposited in or absorbed by sediments, which can be a secondary source of contamination in the ecosystem (Zhang et al., 2012).

According to the Chinese Society for Rare Earth, 1 tonne of rare earth ore produces 9600 to 12,000 m^3 of flue gas comprising of hydrogen fluoride, sulfur dioxide, and sulfuric acid, as well as around 75 m^3 of acidic wastewater, which is dumped into Baotou lakes. The Yellow River is incredibly polluted due to the leakage from such lakes (A publication of the Green Court of Auditors, 2013).

Another material that is hazardous to the life below water is manganese since the waste created by its production is thrown into the sea. Manganese compounds exist naturally in the environment as solids in the soils and small particles in the water; however, they can be toxic if the creatures get exposed to high concentrations (Farjana et al., 2019b).

5.4. SDG 15: Life on land

Establishing aluminum mines, both open and underground, has long-term consequences for plant and animal life. Clear-cutting forests and grasslands cause biodiversity loss, habitat destruction, carbon emissions, and erosion. This happens in countries such as India, Brazil, and China (SCA Community Engagement Fellow Hayden Sloan, 2021).

Table 3
Impacts on society and environment of each material for specified SGDs.

Material	SDG 3	SDG 13	SDG 14	SDG 15
Aluminum (Al)		🟦	🟦	🟦
Boron (B)	🟦			🟦
Chromium (Cr)		🟦	🟦	🟦
Cobalt (Co)	🟦	🟦	🟦	🟦
Copper (Cu)	🟦	🟦		
Manganese (Mn)		🟦	🟦	
Molybdenum (Mo)		🟦	🟦	🟦
Nickel (Ni)		🟦	🟦	
Zinc (Zn)		🟦	🟦	
Rare earth materials	🟦	🟦	🟦	🟦

Due to environmental damage, many refineries have been shuttered in nations like China and Brazil. For example, the Xinfa Group's Jiaokou alumina refinery shut down in Shanxi due to the refinery's dumping of red mud in Xiaoyi city, which contaminated the surrounding river system and crops (Home, 2019).

Furthermore, another material, boron, is utilized in manufacturing wind turbines, having a significant environmental impact. Boron mining pollutes the air and the water, degrading the surrounding landscape and destroying animal habitat (American, 2009).

The establishment of copper mines also affects life on land since abundant land is needed, which means deforestation is also necessary. The consequences of deforestation are habitat destruction, erosion, and biodiversity loss. Moreover, the dust that mines create is later inhaled by animals, causing problems with their respiratory system (Islam et al., 2020).

5.5. Summary

The direct negative impacts on society and the environment categorized due to element extraction are shown in Table 3. The blue highlighted cell depicts the element's direct detrimental impact from mining. Overall, we can see that all the elements impact at least two of the SDGs considered in this study, with cobalt and rare earth metals being the materials affecting the four SDGs.

An indirect negative impact is a side effect that occurs later in a sequence of actions that result in a direct negative impact (Chalmers, 2019). The goals of clean water and sanitation, decent work and economic growth, no poverty, and reduced inequalities goals are jeopardized. Other aims should not be violated to meet the goals of affordable and clean energy, which are occurring and troubling.

6. Conclusions

The analysis carried out in this paper shows that action must be taken to counter the negative effects of wind power generation on society and the environment. Wind power is a renewable source with a low carbon footprint; however, looking at the possible side effects and emission impacts is fundamental.

Several conclusions can be drawn from the investigation performed in the paper to address the current exploitation of the Sustainable Development Goals.

The demand for extracting materials is growing due to reduced labor costs in some countries such as South Africa and China, which leads to increasing environmental degradation and consequences for human health. The increase in consumption is putting more pressure on the mining industries. The recycling of materials or finished goods should be promoted. This is also one of the sustainable development goals, which consists of responsible consumption and production.

The mining industry should formalize its approach so that people are not inhumanely working in the mines. The mining projects should satisfy the socio-environmental criteria. This can be achieved with the government, companies, and policymakers.

The parties involved in using the mined materials, such as the manufacturing of generators, towers, gearboxes, etc., should be aware of the location of the materials and the conditions in which they are extracted.

When wind power projects are planned, they should be analyzed from mining to processing, manufacturing of turbines, and end-use. Moreover, the wind power projects should be updated to fulfill the most sustainable development goals. The responsibility for achieving sustainable goals should not be left only to companies, engineers, or policymakers but should be divided at all levels.

The companies involved in wind power generation should not promote wind power as sustainable, drawing attention only to the positive aspects. Indeed, wind power has its own side effects and still contributes negatively towards economic development, fair trade, modern slavery, etc.

Alternative materials with lower CO_2 emissions for constructing wind turbines should be taken into consideration. The Swedish wood company Modvion has started to produce wooden wind turbine towers (Landqvist and Lind, 2022). Using wood instead of steel gives several advantages: it guarantees a lighter and stronger product; towers can be higher, capturing stronger winds and producing more energy with lower costs; and a more sustainable product as laminated wood makes negative CO_2 emissions for the wind turbine tower since it stores carbon. For this reason, research should focus on using more sustainable materials that are more accessible and that produce less CO_2 emissions.

Therefore, wind power generation should be not only renewable but also sustainable.

This paper does not cover the socio-environmental effects of wind power generation during the end of the life of wind turbines. It can be further taken as future work to check the life cycle assessment of wind power generations from mining and processing until the end of life.

In terms of the circular economy strategy, we expect to obtain results that can lead us to understand the most critical components in terms of faults but also of emissions for production, and possible recycling. This paper is the first step to a more extended study that will include different disciplines coming along to analyze the life expectancy of wind farms. Studying the life cycle of wind farms from several perspectives can give a better overview and help find solutions that cannot be seen using one method only. We expect to obtain results that can lead us to understand how to expand the lifetime of wind farms to utilize the existing components even better.

CRediT authorship contribution statement

Kateryna Morozovska: Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Federica Bragone:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **André Xavier Svensson:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dhruvi Ajit Shukla:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ebba Hellstenius:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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