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# Assessment of Materials and Rare Earth Metals Demand for Sustainable Wind Energy Growth in India

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**Abstract:** Wind energy is an alternative energy generation from non-renewable energy resources. The turbine is used to exploit wind energy. Different components of a wind turbine necessitate different materials and metals. There is a dependency of the materials on foreign countries. To avoid future problems regarding the availability of these materials in India, it is necessary to forecast the quantity and the price of the materials and metals. Thus, this study mainly focuses on the estimation of the raw materials, rare earth, and critical metals used in manufacturing the wind turbine. Two wind turbines of 1.65 MW and 3.45 MW capacity, 78 m and 94 m hub height are considered for the study. The major raw materials are steel, aluminum, copper, cast iron, fiber glass with epoxy resin, and ceramic/glass. The requirement of rare earth elements (Nd) depends on the type of wind turbine direct drive or geared, and the type of generator used in the direct-drive wind turbine. The results estimated the requirement of materials and rare earth elements and the expected price in the future for 100% wind energy production in India.

**Keywords:** wind energy; rare earth elements; critical metals; wind turbine

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## 1. Introduction

Due to the growing population and economy in India, the demand for energy is increasing. More energy resources need to be explored to fulfill the growing demand for energy. Non-renewable energy resources have been used to generate electricity for decades, resulting in major environmental issues. Renewable energy resources are crucial for sustainable development [1], and wind and solar power are the best performing and fastest growing renewable resources. Although there is no direct $CO_2$ emission in electricity generation from wind and solar resources in their life cycle, wind technology emits less $CO_2$ (onshore 7–56 $gCO_2$-eq/kWh, offshore 8–35 $gCO_2$-eq/kWh) as compared to solar technology (CSP 8.8–63 $gCO_2$-eq/kWh, PV-rooftop 26–60 $gCO_2$-eq/kWh, PV-utility 18–180 $gCO_2$-eq/kWh) [2]. The capacity of wind energy is more (400–600 W) compared to solar energy (100–200 W) per square meter of land use [3]. Energy payback time for solar technology is 1–4.1 years [4], whereas the same for wind technology is only 0.69 years [5,6]. Thus, wind energy is seen as a better alternative among the renewable resources for electricity generation. The wind turbine is used to extract wind energy. These wind turbines are categorized as horizontal axis wind turbine (HAWT) and vertical axis wind turbines (VAWT) depending upon the direction of the turbine axis, onshore and offshore wind turbines depending upon the location of wind turbine installation, and geared or direct drive type wind turbine [7,8].

A complete wind farm consists of wind turbines, a foundation, internal cables to connect the individual turbines to the transformer, substation, and external cables to connect the wind power plant to the grid from where the electricity is transmitted to the homes. Few manufacturers like Gamesa Renewable Private Limited, GE India Industrial

Private Limited, Global Wind Power Limited, Kenersys India Private Limited, Leitwind Shriram Manufacturing Limited, and RRB Energy Limited manufacture wind turbines, and few manufacture the components of wind turbine and can be seen in Table 1. A list of materials with components of a wind turbine is also presented in Table 1.

**Table 1.** Components of the wind turbine with the materials.

| Components | Sub-Components | Materials | Manufacturers in India |
|---|---|---|---|
| Rotor | Blade | Glass fibers, Carbon fibers, Epoxy resins, Honeycomb, Balsa wood, Polyester resins, | Suzlon (New Delhi), Vestas India (Chennai), RRB energy limited (New Delhi), ReGen Powertech Pvt. Ltd. (Chennai), Wind World India Ltd. (Mumbai), Inox Wind (Uttar Pradesh). |
| | Hub | Steel, Cast iron. | Suzlon, Vestas India, ReGen Powertech Pvt. Ltd., Inox Wind. |
| Nacelle | Gearbox | Steel, Aluminium, Brass, Chromium, Iron, Manganese, Molybdenum, Nickel. | ReGen Powertech Pvt. Ltd., Suzlon, Wind World India Ltd., Inox Wind. |
| | Anemometer | Stainless steel | |
| | Shaft | Steel | |
| | Generator | Copper, iron, rare earth elements (Neodymium, Dysprosium, Praseodymium, Terbium) | |
| | Others | Aluminium, Chromium, Copper, Iron, Manganese, Molybdenum, Nickel. | |
| Tower | | Steel, Aluminium, Plastic, Copper, Pre-stressed concrete, Chromium, Iron, Manganese, Molybdenum, Nickel. | Suzlon, ReGen Powertech Pvt. Ltd., Wind World India Ltd., Inox Wind. |
| Foundation | | Steel/iron, Concrete. | Wind World India Ltd. |
| Cables | | Plastic, Aluminium, Copper. | |
| Transformer Station | | Steel, Copper. | Suzlon. |

A wind turbine with a gearbox (geared wind turbine) boosts the rotating speed and transfers it to the generator, usually, a double-fed induction generator is used with a higher contribution of copper and iron. Wind turbines that do not have a gearbox (direct drive wind turbines) operate at a constant speed. Here, the generator is directly connected to the rotor. The generator with permanent magnets necessitates the use of rare earth metals, namely neodymium (Nd) and dysprosium (Dy) whereas the electrically excited rotor necessitates the use of copper in substantial quantities. The permanent magnet type generator is the most prevalent generator for the direct-drive wind turbine since it is lightweight and is highly reliable for offshore uses. Direct drive wind turbines are more expensive than geared wind turbines but typically require less maintenance during operation, lowering overall costs. Geared wind turbines, on the other hand, demand frequent maintenance due to the greater number of moving parts. Currently geared wind turbines are employed in 75% of onshore wind turbines since maintenance for an onshore turbine is less difficult than an offshore variant. As offshore wind power is growing, modern advancement in wind turbines suggests a shift to a direct drive or gearless wind turbine technology. Increased direct-drive share contributes to 40% of onshore wind turbines, whereas increased geared wind turbines share provides for 90% of an onshore wind turbine [9]. Direct drive wind turbines are also beneficial to the environment because they do not need an oil cooling technology which reduces the possibility of environmental risk from oil spillage and fire.

The increasing contribution of wind in the energy production mix requires the manufacturing of more wind turbine that further requires substantial raw material like steel, copper, aluminum, carbon and glass fiber, epoxy resins, and rare earth elements such as dysprosium (Dy), neodymium (Nd), praseodymium (Pr). Different materials are used to manufacture various parts of the wind turbine that depends on mechanical properties, namely strength to weight ratio, stiffness, toughness, and fatigue. In general, wind turbines are predominantly made of steel (71%–79% of total turbine mass), fiberglass, resin, or plastic (11%–16%), iron or cast iron (5%–17%), copper (1%), and aluminum (1%) [10]. Mostly used permanent magnets in a wind turbine is NdFeB and made from iron, boron, and rare earth elements (REE) to improve the magnetic property. Wind power technology is a critical technology from the perspective of vulnerability to supply restriction due to the use of Nd and Dy [11]. Kim et al. [12] evaluated the current consumption and stock of critical resources and future requirements of materials for wind power projections. Muilerman and Blonk [13] had suggested that the demand for metals is expected to double over 50 years. The confrontation between the availability of rare earth elements and the global growth of wind power is increasingly disconcerting, and it may eventually taper down the growth of wind power in the future. Under wind energy situations, the existing production capabilities of rare earth elements especially Nd, Pr, and Dy used to manufacture the permanent magnet generators (PMEG), are not compatible with the expected global demand [14]. The demand for Nd is expected to increase globally in the coming 30 years [15]. Deng and Ge [16] analyzed the demand for neodymium and praseodymium using three different scenarios and computing the recycling potential from the end of life. The result suggested that demand ranges from $2.28 \times 10^5$ to $7.88 \times 10^5$ t during 2019–2040. According to Wind Power Monthly, 2018 [17] the concentration of Dy in the generator of Siemens Gamesa Renewable Energy and Gold Wind has been decreased to less than 1%. A prototype of rare-earth free ferrite-based permanent magnet generators has been created by Green Spur [18]. These prototypes are proved successful for 12 MW generators installed for offshore wind turbines and are expected to be successful for 20 MW generators as well by 2022 [19]. Although significant advances have been achieved in minimizing the use of rare earth elements, still we are far away from manufacturing a competitive rare earth free magnet [20] and alternative permanent magnets are unsuitable as these are inefficient and ineffective.

There are few literatures estimating the material demand for wind turbine systems in different locations of the world. Wilbum [21] estimated the future requirement of raw materials for wind turbines in the US by 2030 and suggested that the materials necessary for wind energy electricity generation should not be in limited supply. Imholte et al. [22] performed an estimation of availability in the US and China. The results found that US wind turbines with direct drives could require 4%–12% of maximum light rare earth from Mountain Pass, Bear Lodge, and phosphate rock mines while targets could be achieved by 3%–17% of US light production for direct drive wind energy. Fishman and Graedel [23] estimated the Nd requirement for US offshore wind power. The results found that demand would be 15.5 kt by 2050, and 20% of the demand being reduced by circular utilization. Farina and Anctil [24] analyzed the material requirements for wind turbine in USA and rest of the world until 2050. Further quantified the carbon footprint and cumulative energy demand. The result suggested that steel and REE demand in the US can increase to 511% and 254%–815%, respectively in 2033 as compared to 2018. Zimmermann et al. [25] analyzed the material flows for Germany till 2050 using a statistical method and find that the demand for iron, steel, and aluminum would not surpass 6% of existing consumption. Shammugam et al. [26] evaluated raw material requirements for the wind energy sector in Germany and suggested that Cu and Dy have been highlighted as the most crucial materials due to the risk of supply shortages. The demand for Cu and Dy may exceed a level of 0.2% and 0.6% of respective reserves. Lacal-Arántegui [27] explored the materials used in generators in wind turbines. Li et al. [14] studied the possible issues involving the rare earth demand and supply in different countries till 2050. The results found that an 11-to-26-fold increase in rare earth supply is required to reach worldwide wind-power ambitions. The literatures mainly elaborated on the demand for either selected raw materials or rare earth elements for specific geographical regions and the demand for raw materials for sub-components of a wind turbine. Further work requires to identify the demand for raw materials, critical metals as well as rare earth materials for wind turbines in India and to quantify the expected price of the estimated materials in the future. An increased thrust in the wind sector and higher demand for wind turbines creates a challenge between manufacturers and suppliers in recent years. A transition from non-renewable to 100% renewable and tapping considerable wind power potential in India in the coming years requires forecasting the quantity of different raw materials, rare earth elements, and critical metals available to manufacture the wind turbine and thus support the estimated growth of wind power generation in India. Thus, it is important to quantify and estimate the future demand for the materials used in wind energy to maintain the expected growth.

Thus, the present article deliberates the current wind energy scenario and the potential of wind power in India. The aim of the study is therefore to determine the demand for raw materials, rare earth elements as well as critical metals associated with the short-term and large-term deployment of wind energy in India in the future. In this work, we further performed the economic analysis for the future prediction depending on the past data through inflation rate.

## 2. Material and Methodology

In this study, the demand for raw materials, rare earth, and critical metals with economic analysis are evaluated for the short-term and long-term deployment of wind energy in India. Firstly, the current state and potential of wind energy development has been presented. The installed wind power capacity in India is targeted at 60 GW in 2022 and is expected to grow to 200 GW in 2032. Thus, short-term future demand is forecasted for expected 140 GW capacity additions till 2032 while long-term future demand is assessed for exploiting 695.5 GW wind power potential in India. A list of materials used in different components of the wind turbine is presented for further analysis and material inventory data is presented for two different Vestas wind turbines (V-82 and V-112) with different specifications based on literatures [28,29]. The aim of selecting these two onshore wind turbines is to analyze the material requirements for a wind turbine designed for higher wind conditions (IEC IA)-V112 and medium and low wind conditions (IEC II/III)-V82 and the availability of data about the raw materials. Both wind turbines have the gearbox of planetary/helical type with three stages. These two wind turbines are geared type wind turbines and present only raw materials. Thus, the rare earth elements and critical metal requirement for one MW installed wind capacity is taken from the literatures [30,31]. Based on these collected data, the demand for raw materials, critical metals, and rare earth elements are estimated for short-term and long-term exploitation of wind energy in India. The need for the permanent magnets presents in the direct drive type wind turbine may increase the demand for the Nd [9]. Further, the demand for Nd is forecasted based on the higher share of direct driver geared type wind technology assuming all with permanent magnets. An economic analysis is also performed based on 2016, 2020, and 2022 data. Further 2024 data is predicted considering the inflation rate and 2022 as the base data.

## 3. Current State and Potential of Wind Energy Development in India

India's wind power development is tremendous and proving to become an avenue to overcome the problems of meeting demands for electricity, environmental degradation, emission of greenhouse gases, and depletion of natural resources. As a source of energy, the installed wind power capacity is enormous in India and contributes as the fourth highest installed wind power capacity in the world after China, the US, and Germany. The cumulative installed capacity of wind energy is 40.0 GW out of 104 GW of renewable capacity in 2021 [32]. An increasing trend in the installed capacity of wind energy is presented in Figure 1. It is noticed in Figure 1 that the cumulative installed capacity of wind power has continuously increased from 16.2 GW to 40.0 GW in India between 2011 and 2021 [33].

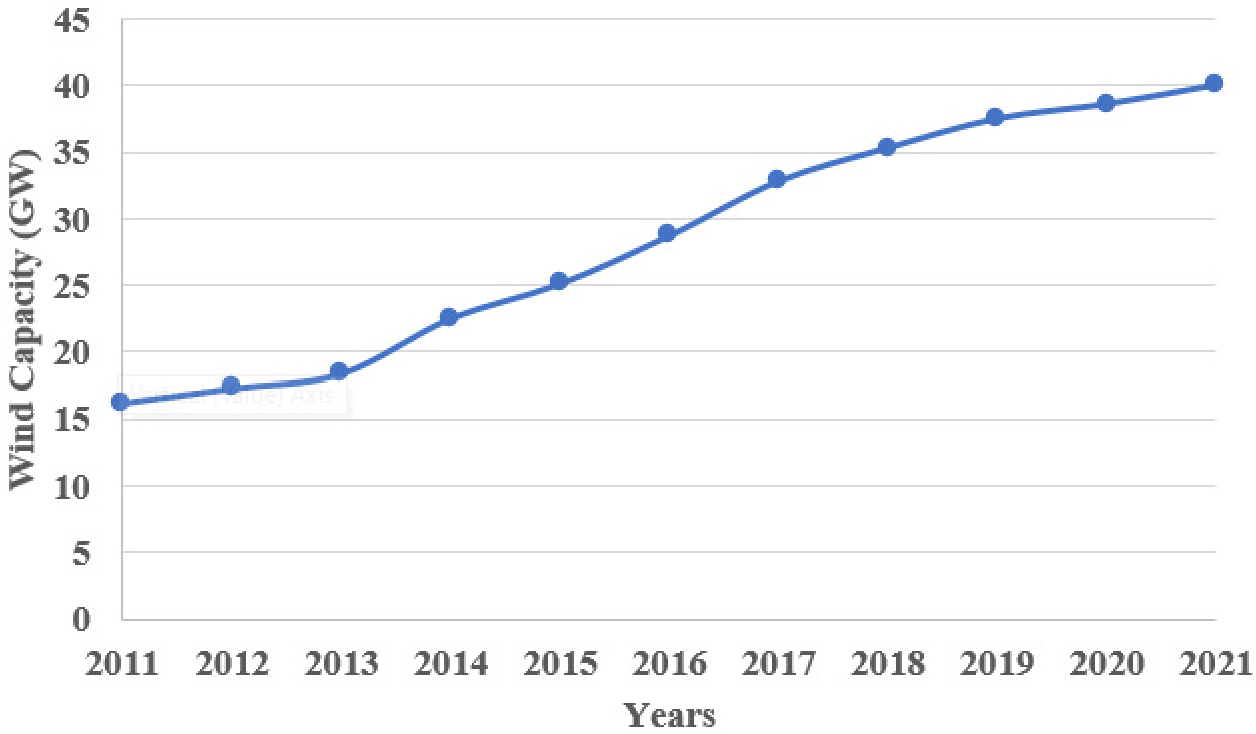


**Figure 1.** Cumulative wind power capacity trend in India between 2011 and 2021 [32,33].

Wind power generation capacity in India has grown significantly, and the pattern of growth could increase in the coming years and the key factor for the strong result of wind power in India is strategic planning of demand and supply made by the government [34]. Due to energy stability and environmental issues, the government is committed to growing wind power in the Indian power generation mix, and also emphasizes policy advancement to encourage investments in the wind energy market in India.

Wind power is renewable, inexhaustible, environmentally friendly, developing technology, and one of the green energy alternatives among all available renewable resources. Renewable energies are claimed to be efficient and sustainable and are used to meet energy requirements at low costs and with higher productivity. India has immense wind energy potential, mostly located in the southern, western, and northern regions of the country (Figure 2). Considering the country's rapidly changing energy scenario, it is necessary to assess the wind power potential to install wind turbines in near future. The potential of wind power varies according to geographic locations, wind density, wind speed variation, and height from ground level. The wind energy potential at 50 m hub height is estimated at 49 GW while it is 102.8 GW at 80 m height. India's northern and north-eastern states are located in the trans-Himalayan region, and the isolated Andaman & Nicobar Islands contribute only 0.5% land availability, while the remaining other states contribute 2% land availability for wind energy estimation [35]. At higher AGL (above ground level), India's wind potential can increase from 302 GW at 100 m AGL to 695.5 GW at 120 m AGL. Total wind power potential at 120 m ground level can be seen in Figure 2 for different states of India [35]. It depicts that India's wind power contributes substantial wind capacity in southern and western states while other states with lower potential are in the developing stage. On basis of land categorization, 695.5 GW wind potential can be produced from 80% potential land availability in wasteland areas, 30% potential land availability in cultivable land areas, and 5% potential land availability in the forest land.

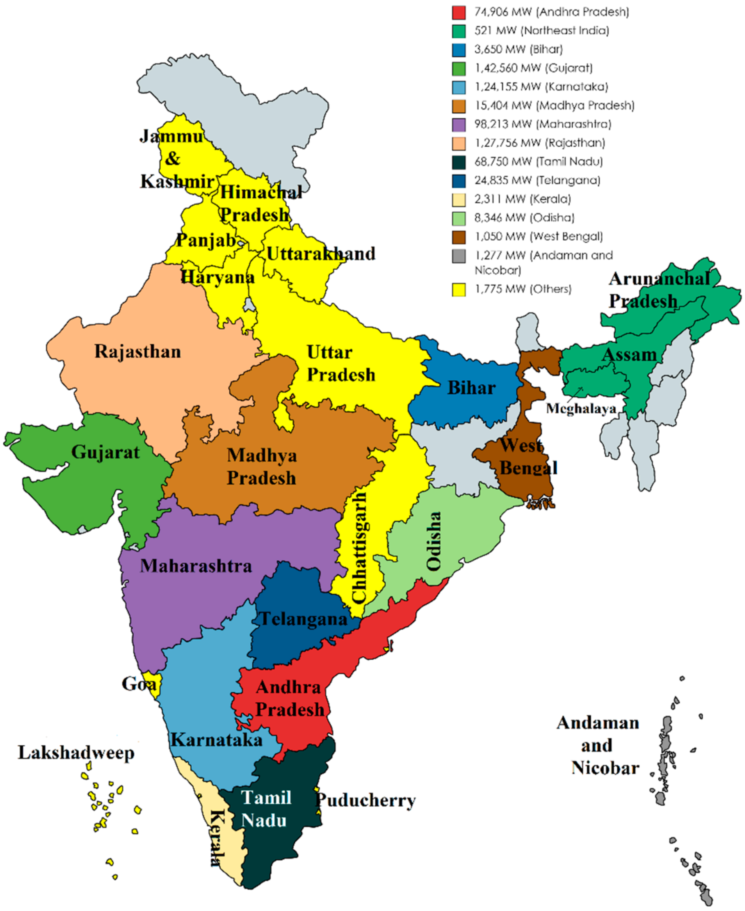


**Figure 2.** Potential of wind energy in India at 120 m AGL [35].

## 4. Mineral Resources in Wind Energy

### *4.1. Raw Materials Used in Wind Energy*

India seems to have strong wind turbine production ability. However, there is still a dependency on foreign vendors because of raw material unavailability. India has witnessed rapid growth in the wind sector in recent years, especially in the utility-scale power generation. In the large utility-scale production of the wind turbine, the availability of raw material is crucial, and its requirement depends on the design of wind turbines and technology. It is necessary to predict the requirement of raw materials used in manufacturing the wind turbine to make the balance between the manufacturer and the suppliers. The quantity and type of raw materials vary according to wind turbine capacity, hub height, rotor diameter, and wind turbine technology. In this study, two wind turbines, namely Vestas V82 and Vestas V112, of different capacities, rotor diameter, and hub height are considered. Both the wind turbines have a three-stage planetary/helical type gearbox. These wind turbines are designed for higher wind conditions (IEC (International Electrotechnical Commission) IA)-V112 and medium and low wind conditions (IEC II/III)-V82 suitable to Indian wind conditions. The two wind turbines have 78 m hub height with 1.65 MW capacities and 94 m hub height with 3.45 MW capacities. Table 2 summarizes about different raw materials used in both wind turbines. The raw materials are only for wind turbine components and sub-components while excluding the foundation, transformer station, and internal and external cable in the study.

**Table 2.** Quantity of raw materials used in a wind turbine [28,29].

| Wind Turbine with 1.65 MW Capacity (V-82) | | | Wind Turbine with 3.45 MW Capacity (V-112) | | |
|---|---|---|---|---|---|
| **Materials** | **Quantity (t)** | **t/MV** | **Materials** | **Quantity (t)** | **t/MW** |
| Steel | 136.6 | 82.79 | Steel and iron materials | 311.6 | 90.34 |
| Aluminium | 3.10 | 1.88 | Aluminium | 4.48 | 1.30 |
| Plastic | 3.00 | 1.82 | Copper | 3.21 | 0.93 |
| Copper | 2.90 | 1.76 | Cast Iron | 70.1 | 20.32 |
| Cast Iron | 29.30 | 17.76 | Electronics/electrics | 3.28 | 0.95 |
| Tool Steel | 14.50 | 8.79 | Lubricants and liquids | 1.86 | 0.54 |
| Stainless Steel | 7.80 | 4.73 | Polymer materials | 17.44 | 5.06 |
| Fibre glass, epoxy | 27.00 | 16.36 | Ceramic/glass | 25.93 | 7.52 |
| Electronics | 2.50 | 1.52 | Rest | 0.45 | 0.13 |
| Oil | 1.30 | 0.79 | | | |

It can be seen in Table 2 that the primary raw material in a wind turbine is steel, and its contribution is higher than other materials about (60% to 71%), followed by cast iron (12% to 16%), fiber glass, and epoxy (11%) and glass/ceramic (6%), tool steel (6%), stainless steel (3%), aluminum (1% to 4%), copper (0.7% to 2%). Some of the contributions are for lubricant or oil, electric or electronics, plastic, or polymers. Commonly used raw materials in these types of wind turbines are steel, aluminum, copper, cast iron, glass fiber, and glass composites. Table 2 accounts for the quantities of the raw materials for the geared-type wind turbine with a water-cooled type of generator but rare earth elements are used to manufacture the PMSG type generator. The critical metals are used to improve the property of raw materials used in wind turbine production. The demand for rare earth elements and critical metals is discussed in the further section.

### *4.2. Rare Earth Elements and Critical Metals Used in Wind Energy*

Rare earth elements are a group of 15 elements from the lanthanides group, scandium, and yttrium elements. Higher density, melting point, and thermal conductivity characterize these 17 elements. These metals and elements are critical due to their scarcity. These elements are necessary for growing economies, but the supply may be challenged due to geographical constraints, geopolitical concerns, market liberalization as well as other circumstances. Based on supply and societal needs, the criticality may change. Praseodymium (Pr), Neodymium (Nd), Terbium (Tb), and Dysprosium (Dy) are the rare earth elements used in wind turbine technology. Nd and Pr are used to improve the magnetic strength, whereas susceptibility to demagnetization of the magnets is improved by Dy and Tb, especially at high temperatures. A typical permanent magnet weighs about 4 t for a wind turbine which contributes Nd as 28.5%, 4.4% Dy, 1% boron, and 66% iron [36]. The use of terbium is currently limited as it has the same function as dysprosium but is significantly more expensive [37]. Praseodymium and terbium are used occasionally and also in small quantities. Permanent magnet generators, which are mostly made of rare earth elements Nd and minor amounts of Dy, have become increasingly popular, particularly in offshore wind turbines. Thus, demand for these elements has risen dramatically in the last two decades. The demand of Nd for 1 MW capacity of the wind turbine is 216 kg [30]. For PMSG type direct drive wind turbine, the quantity of Dy is 17 kg/MW [30].

Other critical metals used for wind turbine technology are chromium (Cr), manganese (Mn), molybdenum (Mo), and nickel (Ni). These critical metals are used as an alloy. In wind turbines, Mo is used with high-strength steel, and Ni is used as an alloy in stainless steel. Stainless steel with 12%–18% Cr and super-stainless steel with 12%–30% Cr and 7%–10% Ni add strength, hardness, and toughness to their alloys. It also resists corrosion and inhibits steel abrasion, as well as reduces oxidation. In India, nickel is present in form of oxides, sulfides, and silicates, and the reserve is estimated as 189 Mt [33]. The reserves for manganese ore and molybdenum are 495.87 Mt and 19.37 Mt, respectively [33,34]. The demand for these critical metals in kg for one MW has been presented in Figure 3. It is observed from Figure 4 that the demand for Mn and Mo is less compared to Ni and Cr.

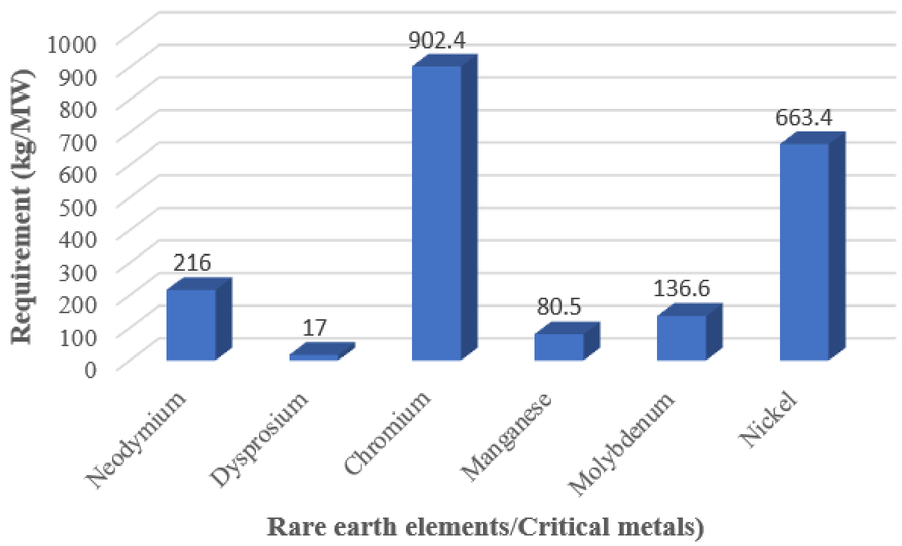


**Figure 3.** Rare earth and special metal demand for wind turbine technology estimated in kg/MW [30,31].

## 5. Results

To manufacture the wind turbine components and sub-components in the required quantity and quality, the raw material must be available and necessary to avoid dependency on either raw materials or larger and heavy wind turbine components from foreign countries for cost-effective manufacturing.

### *5.1. Estimation of Raw Materials in Short and Long-Term Production*

India has a huge potential for wind power (695.5 GW). The target of wind power in India is increasing with time. The target is 60 GW by 2022 and 200 GW by 2032. If we consider the target of wind power in India, the capacity to be developed between 2022 and 2032 is 140 GW. Over the past decades, the technologies of wind turbines are experienced continuous advancement. As different technologies use different components in a wind turbine, thus different raw materials and critical metals are used to manufacture it. So, it is important to ensure the availability of raw materials, rare earth elements, and critical metals for the cost-effective manufacturing of wind turbine components. Considering two wind turbines of Vestas for 1.65 MW and 3.45 MW wind capacity, the requirements of the raw materials are estimated here. For the short-term and long-term basis, the raw material requirement in India can be seen in Table 3. It presents mostly used raw materials in a wind turbine.

**Table 3.** Estimate wind turbine material requirement.

| Materials | Wind Turbine with 1.65 MW Capacity (V-82) | | Wind Turbine with 3.45 MW Capacity (V-112) | |
|---|---|---|---|---|
| | Quantity (Mt) 2022–2032 (140 GW) | Quantity (Mt) 695.5 GW | Quantity (Mt) 2022–2032 (140 GW) | Quantity (Mt) (695.5 GW) |
| Steel | 11.6 | 57.6 | 12.65 | 62.8 |
| Aluminium | 0.266 | 1.32 | 0.182 | 0.90 |
| Copper | 0.252 | 1.25 | 0.13 | 0.65 |
| Cast Iron | 2.5 | 12.4 | 2.84 | 14.13 |
| Tool Steel | 1.232 | 6.12 | - | - |
| Stainless Steel | 0.658 | 3.27 | - | - |
| Fibre glass, epoxy | 2.296 | 11.4 | - | - |
| Ceramic/Glass | - | - | 1.05 | 5.23 |

From the estimated analysis, it is found that material requirement depends on different capacities, rotor diameter, and the hub height of the wind turbine. The strongest requirement is for steel from the higher capacity wind turbine, representing a 9% increase from 1.65 MW capacity.

*5.2. Estimation of Rare Earth and Critical Metals in Short and Long-Term Production*

Permanent magnets are made of rare earth elements. Especially Nd and Dy are used as PMSG in direct-drive wind turbines. The increased need for PMSG in the wind industry necessitates an increase in the demand for Nd and Dy due to a shift in generator technology. The availability of these elements in India may become a big issue if imports from other nations are restricted in the future. So, Nd and Dy are quantified for future requirements. The critical metals used as an alloy to improve the strength, and corrosion properties are estimated for short-term and long-term wind turbine manufacturing and can be seen in Table 4 along with rare earth metals neodymium and dysprosium. In order to tap 100% wind potential in India, the estimated quantity of Nd and Dy required is 150,228 t and 11,823.5 t, respectively. The estimated quantity of critical metals like Cr and Ni is even higher as compared to Mn and Mo. The estimated quantity is 627,619.2 t for Cr, 461,394.7 t for Ni, 95,005.3 t for Mo, and 55,987.8 t for Mn.

**Table 4.** Critical/Rare earth metal estimate in wind power in India.

| Rare Earth Elements and Critical Metals | Quantity in t 2022–2032 (140 GW) | Quantity in t for 695.5 GW |
|---|---|---|
| Neodymium | 30,240 | 150,228 |
| Dysprosium | 2380 | 11,823.5 |
| Chromium | 126,336 | 627,619.2 |
| Manganese | 11,270 | 55,987.8 |
| Molybdenum | 19,124 | 95,005.3 |
| Nickel | 92,876 | 461,394.7 |

The requirement of rare earth elements completely depends on the technology either geared or direct drive wind turbine. The demand for Nd may increase by 48% or decrease by 65% according to the higher share of direct drive or geared wind turbines [9]. Figure 4 shows the forecasted requirement of Nd in the future. It indicates that demand for Nd could increase compared to the base case of increasing the demand for the direct-drive wind turbine.

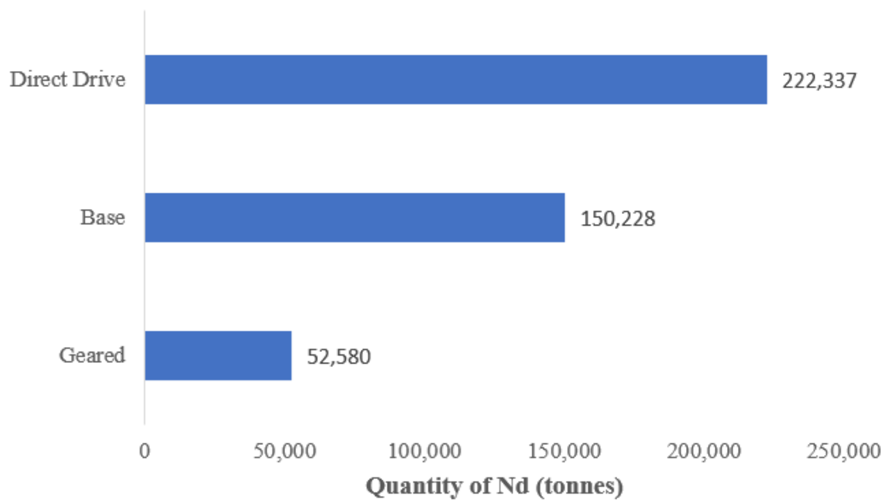


**Figure 4.** Variation in demand of Nd.

### 5.3. Economic Analysis of Raw Materials, Rare Earth and Critical Metals

The availability of raw materials required for component manufacturing in sufficient quantity and of requisite quality at a reasonable price is critical to cost competitiveness. In the way of sustainable energy generation, it is important to analyze the price of materials and metals used in the manufacturing of wind turbines. Table 5 represents the price of materials for the years 2016, 2020, 2022, and 2024. It is seen that the price of the materials is increased for steel (13.3%), aluminum (80%), copper (65.6%), nickel (118%), chromium (32.93%), and molybdenum (131.5%) from 2020 to 2022. However, the recent price surge in REE indicates that neodymium and dysprosium prices are increased by a whopping 243% and 103%, respectively from 2020 to 2022, mainly due to the skewness exists between the demand and supply of these REE [38,39]. The data for 2024 shown in Table 5 is calculated based on past inflation considering 2022 as the base year. The average inflation rate in US$ is 2.96% per year between 2020 and 2022. However, if the skewness in the demand supply of REE exists in the future, the estimated price for REE in 2024 would surpass the inflation rate and would be even higher.

**Table 5.** Price of material in 2024 considering 2022 data [38–44].

| Materials | Price of Materials (US$/t) | | | |
|---|---|---|---|---|
| | **2016** | **2020** | **2022** | **2024** |
| Steel | 519.95 | 687.92 | 779.6 | 826.44 |
| Aluminium | 1772.52 | 1962.1 | 3538 | 3750.55 |
| Copper | 4863 | 6181 | 10,237.59 | 10,852.63 |
| Nickel | 9595 | 14,000 | 30,644 | 32,484.97 |
| Neodymium | 40,000 | 52,963.8 | 181,590 | 192,499.23 |
| Dysprosium | 198,000 | 260,000 | 518,288.13 | 549,424.89 |
| Chromium | 10,955.87 | 8708.3 | 11,576.36 | 12,271.82 |
| Molybdenum | 14,400 | 20,000 | 46,300 | 49,081.53 |

The total price for each material is estimated for years 2022 and 2024 and can be seen in Table 6. For price estimation, the maximum estimate quantity of materials for 695.5 GW wind power potential is considered.

**Table 6.** Estimated price analysis.

| Materials | Estimated Price for 2022 (Billion US$) | Expected Price for 2024 (Billion US$) |
|---|---|---|
| Steel | 49 | 52 |
| Aluminium | 4.7 | 4.9 |
| Copper | 12.8 | 13.6 |
| Neodymium | 27.28 | 28.9 |
| Dysprosium | 6.13 | 6.46 |
| Chromium | 7.27 | 7.7 |
| Molybdenum | 4.4 | 4.66 |
| Nickel | 14.14 | 14.99 |

## 6. Discussion

The materials used in wind energy are mainly steel, aluminum, copper, cast iron, fiber glass, epoxy resin, glass/ceramic, stainless-steel, rare-earth elements (Nd, Dy), and critical metals (Ni, Cr, Mn, Mo). India has vast mineral potential with mining leases granted for a longer duration of 20 to 30 years [45].

In FY20, steel production and consumption in India was 101.05 Mt and 100 Mt, respectively and imports of iron and steel increased at a compound annual growth rate (CAGR) of 4.02% during FY16-FY20. India's current steel production capacity is 140 MTPA with 300 MTPA predicted by 2030-31 [46]. Bauxite reserves for aluminum production in India were 3896 Mt [47]. India's aluminum production share is 5.33% of global production and production is increased at a CAGR of 10.62% during FY16-FY20 and stood at 3.6 Mt in FY20 [45]. Indian copper industry is about 0.66 Mt which is only 3% of the world copper market [48]. India's rare earth reserve is 6.9 Mt accounting for around 6% of global reserves in 2020 while the mine production is 3000 Mt [49]. Monazite is the primary resource (12.47 Mt) in India for rare earths and thorium. Extracting dysprosium from monazite and providing high-grade dysprosium can help India economically. The current production of neodymium matches with extent of India's existing potential. India, on the other hand, might gain Japan's experience in creating NdFeB magnets in exchange for raw resources, instead of exporting monazite ore [50]. In India, nickel is present in form of oxides, sulfides, and silicates, and the reserve is estimated as 189 Mt [51]. The reserves for manganese ore and molybdenum are 495.87 Mt and 19.37 Mt respectively [52,53].

The demand for mostly used raw materials in wind turbine production in India till 2032 would be steel (11.6–12.65 Mt), aluminum (0.182–0.266 Mt), Copper (0.13–0.252 Mt), cast iron (2.5–2.84 Mt), tool steel (1.232 Mt), stainless steel (0.658 Mt), fiber glass with epoxy (2.296 Mt) and ceramic/glass (1.05 Mt), Nd (30,240 t), Dy (2380 t), Cr (126,336 t), Mn (11,270 t), Mo (19,124 t) and Ni (92,876 t).

In order to tap 100% wind power potential in India, the estimated quantity for mostly used raw materials are steel (58–63 Mt), aluminum (0.9–1.32 Mt), copper (0.65–1.25 Mt), cast iron (12.4–14.3 Mt), fiber glass with epoxy resin (11.4 Mt), ceramic/glass (5.23 Mt). Neodymium (Nd) and dysprosium (Dy) are the rare earth elements generally used in manufacturing PMSG for the direct-drive wind turbine. The estimated requirement of Nd and Dy is 150,228 t and 11,824 t, respectively. The quantity of Nd may increase or decrease in the future depending on the increased share of direct drive or geared wind turbines. The requirement of Nd may fluctuate between 52,580 t to 222,337 t. The demand for critical metals used in a wind turbine is Cr (627,619.2 t), Mn (55,987.8 t), Mo (95,005.3 t), and Ni (461,394.7 t).

Indian manufacturers produce the components like blade, hub, wind turbine generator, gearbox, tower, foundation, etc. The manufacturers like Siemens Gamesa, Suzlon, Vestas, Inox Wind, GE India, and Envision had a share of about 96% of the wind energy market share in 2019 [54]. A plan for a new nacelle and hub manufacturing facility by Vestas could make India a global production hub [55].

An assessment is carried out to evaluate if the current metals and minerals production capacity is sufficient in India to meet the short-term (considering 140 GW wind energy production by 2032) and long-term potential (considering 695.5 GW wind energy production). It has been found that the current steel, aluminum, and chromium production capacity in India is sufficient to meet both the short and long-term demands due to wind turbine production. However, the current copper, nickel, manganese, and molybdenum production capacity in India is not enough to meet the long-term demand from the wind turbine sector. Current stainless steel production capacity in India is sufficient for short-term demand but would not be enough for long-term demand estimated for wind turbine production. The rear earth elements like neodymium and dysprosium required for wind turbine production are not abundantly available in India and hence, the Indian wind turbine manufacturers are dependent on the import of these materials.

## 7. Conclusions and Recommendations

Due to the limiting resources of non-renewable and greenhouse gas, it is necessary to move towards 100% renewable energy. Among all the renewable energy options available in India, wind energy is considered clean energy. The wind energy trend in India is increasing continuously. However, statistics show that only 38.9%, 13.2%, and 5.8% of the total wind potential corresponding to 80 m, 100 m, and 120 m above ground level (AGL) have been installed in India so far. Hence, more wind turbine installation is required to tap most of the total wind power potential of India (695.5 GW). In this study, the quantity demand of raw materials, rare earth elements (REE), and critical metals are estimated and analyzed in detail. The cost is estimated according to the requirement of the materials for cost-competitive wind power for long-term prediction on basis of short-term estimation. Short-term cost is based on 2020 data, and long-term cost is based on expected 2024 cost data, the economic analysis is performed for different materials and is presented in this study.

- Mostly used raw material in wind turbine production is steel, cast iron, aluminum, copper, fiber glass with epoxy resin, and glass/ceramics. The tower is generally made of steel and contributes the highest contribution 60% to 71%. Other parts except tower and blade contributes cast iron 12% to 16%, aluminum 1% to 4%, copper 0.7% to 2%. Blade materials are fiber glass and epoxy resin with 11% or glass/ceramics with 6%, and polymers of 4%.
- The estimated analysis revealed that the material demands vary depending upon the different wind turbine systems due to different capacities, rotor diameter, hub height, and technologies of the wind turbine. The demand for rare earth elements (REE) like neodymium varies depending upon the direct drive and geared type wind turbine. There is already high pressure on the supply chains of REE. In addition, there is a strong pressure on REE as it is also needed in electro-mobility. Hence, the less availability of the REE can jeopardize wind power growth.
- The price for different materials has a lesser difference between 2016 and 2020, but a drastic increase can be seen between 2020 to 2022. The predicted price of the material for 2024 is calculated considering the average inflation rate of 2.96% and base year data 2022.
- In order to tap 100% wind power in India, the contribution of price is higher for steel, copper, nickel, and neodymium.
- Study of circular economy is used to make better use of components throughout the life cycle. A systematic analysis is required for wind turbines in their approach to sustainability. This will be analyzed in a future study for wind turbine components and materials.

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## Abbreviation

| | |
|---|---|
| AGL | Above ground level |
| CSP | Concentrated Solar Power |
| GHG | Greenhouse gas |
| HAWT | Horizontal axis wind turbine |
| IEC | International Electrotechnical Commission |
| MNRE | Ministry of New and Renewable Energy |
| NIWE | National Institute of Wind Energy |
| PMSG | Permanent magnet generators |
| PV | Photovoltaics |
| REE | Rare earth element |
| VAWT | Vertical axis wind turbine |
| MTPA | Million t per annum |
| NdFeB | Neodymium Iron Boron Magnets |

## References


1. Kumar, S.; Madlener, R. $CO_2$ emission reduction potential assessment using renewable energy in India. *Energy* **2016**, *97*, 273–282. [CrossRef]
2. Bruckner, T.; Fulton, L.; Hertwich, E.; McKinnon, A.; Perczyk, D.; Roy, J.; Schaeffer, R.; Schlömer, S.; Sims, R.; Smith, P.; et al. Technology-specific Cost and Performance Parameters [Annex III]. In *Climate Change 2014: Mitigation of Climate Change*; Cambridge University Press: Cambridge, UK, 2014; pp. 1329–1356.
3. Khaleghi, S.; Moghaddam, R.K. Parameters optimization to maximize the wave energy extraction. In Proceedings of the 2015 International Congress on Technology, Communication and Knowledge, Mashhad, Iran, 11–12 November 2015; pp. 260–267. [CrossRef]
4. Bhandari, K.P.; Collier, J.M.; Ellingson, R.J.; Apul, D.S. Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis. *Renew. Sustain. Energy Rev.* **2015**, *47*, 133–141. [CrossRef]
5. Bonou, A.; Laurent, A.; Olsen, S.I. Life cycle assessment of onshore and offshore wind energy-from theory to application. *Appl. Energy* **2016**, *180*, 327–337. [CrossRef]
6. Gomaa, M.R.; Rezk, H.; Mustafa, R.J.; Al-Dhaifallah, M. Evaluating the Environmental Impacts and Energy Performance of a Wind Farm System Utilizing the Life-Cycle Assessment Method: A Practical Case Study. *Energies* **2019**, *12*, 3263. [CrossRef]
7. Verma, S.; Paul, A.R.; Jain, A. Performance investigation and energy production of a novel horizontal axis wind turbine with winglet. *Int. J. Energy Res.* **2022**, *46*, 4947–4964. [CrossRef]
8. Verma, S.; Paul, A.R.; Jain, A.; Alam, F. Numerical investigation of stall characteristics for winglet blade of a horizontal axis wind turbine. *E3S Web Conf.* **2021**, *321*, 03004. [CrossRef]
9. Hund, K.; La Porta, D.; Fabregas, T.P.; Laing, T.; Drexhage, J. *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*; World Bank: Washington, DC, USA, 2020.
10. Moné, C.; Hand, M.; Bolinger, M.; Rand, J.; Heimiller, D.; Ho, J. *2015 Cost of Wind Energy Review*; Technical Report No. NREL/TP-6A20-66861; National Renewable Energy Lab: Golden, CO, USA, 2017.
11. Miyamoto, W.; Kosai, S.; Hashimoto, S. Evaluating Metal Criticality for Low-Carbon Power Generation Technologies in Japan. *Minerals* **2019**, *9*, 95. [CrossRef]
12. Kim, J.; Guillaume, B.; Chung, J.; Hwang, Y. Critical and precious materials consumption and requirement in wind energy system in the EU 27. *Appl. Energy* **2015**, *139*, 327–334. [CrossRef]
13. Muilerman, H.; Blonk, H. *Towards a Sustainable Use of Natural Resources*; Stichting Natuur en Milieu: Utrecht, The Netherland, 2001; pp. 1–18.
14. Li, J.; Peng, K.; Wang, P.; Zhang, N.; Feng, K.; Guan, D.; Meng, J.; Wei, W.; Yang, Q. Critical rare-earth elements mismatch global wind-power ambitions. *One Earth* **2020**, *3*, 116–125. [CrossRef]
15. García-Olivares, A.; Ballabrera-Poy, J.; García-Ladona, E.; Turiel, A. A global renewable mix with proven technologies and common materials. *Energy Policy* **2012**, *41*, 561–574. [CrossRef]
16. Deng, X.; Ge, J. Global wind power development leads to high demand for neodymium praseodymium (NdPr): A scenario analysis based on market and technology development from 2019 to 2040. *J. Clean. Prod.* **2020**, *277*, 123299. [CrossRef]
17. Dodd, J. Rethinking the Use of Rare-Earth Elements. *Wind Power Monthly*, 30 November 2018. Available online: https://www.windpowermonthly.com/article/1519221/rethinking-use-rare-earth-elements (accessed on 20 October 2020).
18. Green Spur Renewables. Introducing the GreenSpur Wind Generator. 2020. Available online: https://www.greenspur.co.uk/ (accessed on 20 October 2020).
19. Snieckus, D. Offshore Wind Turbine 20MW Generator Ready within Three Years. 22 November 2019. Available online: https://www.rechargenews.com/ (accessed on 20 October 2020).
20. Coey, J.M.D. Perspective and Prospects for Rare Earth Permanent Magnets. *Engineering* **2020**, *6*, 119–131. [CrossRef]
21. Wilburn, D.R. Wind energy in the United States and materials required for the land-based wind turbine industry from 2010 through 2030. In *Scientific Investigations Report*; US Department of the Interior, US Geological Survey: Washington, DC, USA, 2011; p. 5036.
22. Imholte, D.D.; Nguyen, R.T.; Vedantam, A.; Brown, M.; Iyer, A.; Smith, B.J.; Collins, J.W.; Anderson, C.G.; O'Kelley, B. An assessment of U.S. rare earth availability for supporting U.S. wind energy growth targets. *Energy Policy* **2018**, *113*, 294–305. [CrossRef]
23. Fishman, T.; Graedel, T.E. Impact of the establishment of US offshore wind power on neodymium flows. *Nat. Sustain.* **2019**, *2*, 332–338. [CrossRef]
24. Farina, A.; Anctil, A. Material consumption and environmental impact of wind turbines in the USA and globally. *Resour. Conserv. Recycl.* **2022**, *176*, 105938. [CrossRef]
25. Zimmermann, T.; Rehberger, M.; Gößling-Reisemann, S. Material Flows Resulting from Large Scale Deployment of Wind Energy in Germany. *Resources* **2013**, *2*, 303–334. [CrossRef]
26. Shammugam, S.; Gervais, E.; Schlegl, T.; Rathgeber, A. Raw metal needs and supply risks for the development of wind energy in Germany until 2050. *J. Clean. Prod.* **2019**, *221*, 738–752. [CrossRef]
27. Arántegui, R.L. Materials use in electricity generators in wind turbines—State-of-the-art and future specifications. *J. Clean. Prod.* **2015**, *87*, 275–283. [CrossRef]

28. Schmidt, A. Life Cycle Assessment of Electricity Produced from Onshore Sited Wind Power Plants Based on Vestas V82-1.65 MW Turbines. Vestas Reports. 2016. Available online: https://www.vestas.com/~{}/media/vestas/about/sustainability/pdfs/lca%20v82165%20mw%20onshore2007 (accessed on 21 August 2020).
29. Razdan, P.; Garrett, P. *Life Cycle Assessment of Electricity Production from an Onshore V112-3.45 MW Wind Plant*; Vestas Wind System: Aarhus, Denmark, 2017.
30. Carrara, S.; Alves, D.P.; Plazzotta, B.; Pavel, C. *Raw Materials Demand for Wind and Solar PV Technologies in the Transition Towards a Decarbonised Energy System, EUR 30095 EN*; Publications Office of the European Union: Luxembourg, 2020.
31. Moss, R.L.; Tzimas, E.; Kara, H.; Willis, P.; Kooroshy, J. *Critical Metals in Strategic Energy Technologies*; Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies. JRC Scientific and Technical Reports; Publications Office of the European Union: Luxembourg, 2011.
32. Ministry of New and Renewable Energy. Physical Progress 2020–2021. GOI. 2021. Available online: https://mnre.gov.in/the-ministry/physical-progress (accessed on 10 October 2020).
33. International Renewable Energy Agency. *Renewable Capacity Statistics 2021*; International Renewable Energy Agency (IRENA): Abu Dhabi, United Arab Emirates, 2021.
34. Dawn, S.; Tiwari, K.; Goswami, A.K.; Singh, A.K.; Panda, R. Wind power: Existing status, achievements and government's initiative towards renewable power dominating India. *Energy Strategy Rev.* **2019**, *23*, 178–199. [CrossRef]
35. National Institute of Wind Energy. *India's Wind Potential Atlas at 120 m agl*; Under Ministry of New and Renewable Energy, Government of India: New Delhi, India, 2019.
36. Rabe, W.; Kostka, G.; Smith Stegen, K. China's supply of critical raw materials: Risks for Europe's solar and wind industries? *Energy Policy* **2017**, *101*, 692–699. [CrossRef]
37. Reimer, M.V.; Schenk-Mathes, H.Y.; Hoffmann, M.F.; Elwert, T. Recycling decisions in 2020, 2030, and 2040—When can substantial NdFeB extraction be expected in the EU? *Metals* **2018**, *8*, 867. [CrossRef]
38. Magnosphere Price Development for Neodymium Magnets. Available online: https://www.magnosphere.co.uk/price-development-for-neodymium-magnets (accessed on 3 May 2022).
39. SMM. Rare Earth Metals: Dysprosium. 2022. Available online: https://www.metal.com/Rare-Earth-Metals/201102250389 (accessed on 3 May 2022).
40. Ministry of Mines. *Non-Ferrous Minerals & Metals, Aluminium*; Government of India: New Delhi, India, 2022.
41. Ministry of Mines. *Non-Ferrous Minerals & Metals, Copper*; Government of India: New Delhi, India, 2022.
42. Trading Economics. Nickel. 2022. Available online: tradingeconomics.com (accessed on 3 May 2022).
43. SMM. Chromium. April 2022. Available online: https://www.metal.com/price/Minor%20Metals/Chromium (accessed on 3 May 2022).
44. Trading Economics. Molybdenum. 2022. Available online: tradingeconomics.com (accessed on 3 May 2022).
45. Metals and Mining. *India Brand Equity Foundation*; IBEF: New Delhi, India, 2020.
46. Indian Brand Equity Foundation. Indian Steel Industry Report. 2021. Available online: https://www.ibef.org/industry/steel.aspx (accessed on 20 March 2022).
47. Ministry of Mines, India Bureau of Mines. *Indian Minerals Yearbook 2019, Bauxite*; Government of India: New Delhi, India, 2020.
48. Ministry of Mines, India Bureau of Mines. *Non-Ferrous Minerals and Metals*; Government of India: New Delhi, India, 2021.
49. U.S. Geological Survey. *Mineral Commodity Summaries*; U.S. Geological Survey: Washington, DC, USA, 2021.
50. Zangeneh, S. *State of India's Rare Earth Industry—Understanding India's Current Position*; ISSSP: Bangalore, India, 2018.
51. Ministry of Mines, India Bureau of Mines. *Indian Minerals Yearbook 2020, Nickel*; Government of India: New Delhi, India, 2021.
52. Ministry of Mines, India Bureau of Mines. *Indian Minerals Yearbook 2019, Manganese Ore*; Government of India: New Delhi, India, 2020.
53. Ministry of Mines, India Bureau of Mines. *Indian Minerals Yearbook 2019, Molybdenum*; Government of India: New Delhi, India, 2021.
54. Bloomberg NEF. *India's Top Wind Suppliers in 2019*; Bloomberg NEF: London, UK, 2020.
55. Vestas. Vestas to Establish New Nacelle and Hub Assembly Factory in India, Quadrupling Local Manufacturing Jobs. 2019. Available online: https://www.vestas.com/en/media/company-news/2019/vestas-to-establish-new-nacelle-and-hub-assembly-factor-c2963168 (accessed on 21 March 2022).