Permanent Magnets in Offshore Wind: State of the Art, Future Trends and Risk

Amir R. Nejad
Department of Marine Technology
Norwegian University of Science and Technology
Trondheim, Norway
Amir.Nejad@ntnu.no

Mihaela Ibrion
Department of Marine Technology
Norwegian University of Science and Technology
Trondheim, Norway
Mihaela.Ibrion@ntnu.no

***Abstract*—This paper presents an overview, state-of-the-art, development trends and associated risks of the rare earth permanent magnets usage in the offshore wind industry. The offshore wind is set for a major growth and demand for permanent magnets is expected to rise dramatically. This study puts forward a critical analysis and brings to attention discussions with pros and cons about the rare earth element (REE) in offshore wind. It also highlights the risks associated with REE permanent magnets including: a large increase in demand; concentration of supply chain; environmental hazards; market volatility and high prices; specialized workforce; constraints linked to patents; role of national policies, acts and international policies; and availability concerns. Moreover, it presents innovative technologies to reduce or substitute REE in magnet, although challenging to achieve similar performance characteristics. At the system level, use of hybrid system can also contribute significantly to lighter generator and thus REE reduction.**

***Index Terms*—permanent magnet, rare earth elements (REE), offshore wind, Neodymium and Dysprosium, risk**

I. INTRODUCTION & RESEARCH APPROACH

As our societies become more digital, more energy-efficient and climate-neutral oriented, the demand for critical materials, particularly, rare earth elements (REE) will increase in the coming decades. The green transition is metal and mineral intensive as large quantities are required to meet the global needs about mobile technology, electrical vehicles, renewable energy production such as wind and solar power, battery production and energy infrastructure [1], [2].

The REE are valuable in many industries and applications, and offshore wind offers an illustrative example, particularly, due to the permanent magnets [3]. Fig. 1 presents an overview of the global magnet rare earth elements by different sectors and as per the three International Energy Agency (IEA) scenarios [4].

The present work aims to offer a compact overview about the usage of REE permanent magnets in the offshore wind industry. Furthermore, it targets to put forward insights about the future trends and sources of risk associated with the REE permanent magnets in offshore wind. The study approach is outlined in Fig. 2. As for methodology, the present study analyses scientific literature, industrial practices, expert views through both a historical and current perspective, a critical analysis, and discussions with pros and cons about the usage of REE magnets in offshore wind and the way forward.

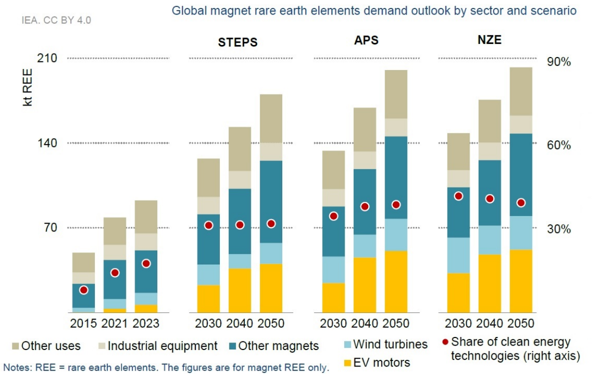

Fig. 1. Global magnet rare earth elements, different sectors and 3 IEA scenarios; the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS) and the Net Zero Emissions by 2050 (NZE) Scenario [4].

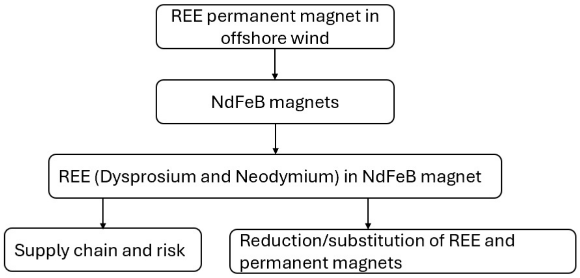

Fig. 2. Study approach.

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II. RARE EARTH PERMANENT MAGNETS IN OFFSHORE WIND

Permanent magnets are those magnets that can maintain their magnetism for a long time, are not easily magnetized/demagnetized, and their polarity will not change. However, within an environment with high reverse magnetic field strength or exposed to heat above Curie temperature, the magnetism of permanent magnet will decrease or even can disappear [5]. A rare earth permanent magnet is a strong permanent magnet made from alloys of particular rare earth elements (REEs). The rare earth elements (REE)s are grouped in Heavy REEs (HREE)s and Light REEs (LREE)s. The REEs are part of the list of the EU Critical Raw Materials (CRM)s. Fig. 3 - in Appendix - illustrates the world map with the main global producers of the CRMS, including REEs, in 2023 [6]. In Fig. 3 can be observed that China is one of the largest supplier of CRMs in the world, including REEs.

The properties of REE make the magnets much stronger and durable than non-REE magnets. Neodymium (NdFeB) and Samarium Cobalt (SmCo) are the most common type of REE magnets. The maximum working temperature for neodymium magnets is about 140 °C, and for the SmCo magnets is about 300 °C [5]. Other REEs such as Dysprosium and Terbium are key additives to the Neodymium (NdFeB) permanent magnets [7].

The use of rare earth metals in the permanent magnets of generators is a standard practice among wind turbine manufacturers. Rare earth elements provide important advantages, as they significantly enhance the efficiency of generators and improve their compatibility with the power grid [8]. Permanent magnets are an integral part of direct drive turbines in offshore wind. As per Vattenfall [9], the wind turbines depending on their size, can house between one to eight tons of permanent magnet [9]. Large offshore wind turbines require a big amount of permanent magnet [3]. According to some experts in the field a large direct drive offshore wind turbine can require more than 5 tons of magnet in which REEs represent about 30 % of the magnet weight i.e. 1.5 tons [10]. Vestas as one of the major wind turbine manufacturers employs two types of drivetrain concepts: the conventional geared drivetrains and the gearless direct-drive systems [8]. Notably, the quantity of rare earth elements used in conventional geared drivetrains is up to 10 times lower comparative with the quantity required for direct-drive generator systems [8].

A. Neodymium-Iron-Boron (NdFeB) magnet

Neodymium magnet, known also as NdFeB magnet, basically, is a tetragonal crystal composed of neodymium, iron, and boron ($Nd_2Fe_{14}B$) [11]. As per the historical trajectory, the neodymium-iron-boron (NdFeB) permanent magnet was invented in the early 1980s. In 1983 at the Magnetism and Magnetic Material Conference in Pittsburgh, it was very intriguing that John Croat as a project manager in General Motors US, and Masato Sagawa, project leader at Sumitomo Japan, surprised each other by announcing their discovery of the NdFeB magnet at the same conference. It seems that both companies and their project leaders have been working secretly and independently on the same technology and raced to commercialize the technology of the NdFeB magnet with a great potential for a huge market [12]. At that time, the best permanent magnets were considered to be the samarium-cobalt magnets, strong and reliable magnets, but very expensive.

Nowadays, around 95 % of permanent magnets are Neodymium-Iron-Boron magnets [12]. Moreover, the neodymium magnet has been seen as one of the strongest magnets in the market and among the most lasting kind of magnet in the world [11]. Both Sumitomo Special Metals and General Motors came up with independent ways of manufacturing the Neodymium magnet: sintering process and the melt-spinning process, respectively. The sintered Neodymium magnets aimed to have more structural strength or resilience, and the General Motors magnets could be produced much cheaper. However, the sintered-magnet market has been much bigger than the melt-spinning or bonded-magnet market: the sintered-magnet has been used primarily for bigger motors, wind-turbine generators, Magnetic Resonance Imaging (MRI)s, and most of the electric-vehicle motors [12]. General Motors patented its method in the North America, and Sumitomo with the patents for the composition Neodymium-Iron-Boron in Japan and Europe. They finally reached agreements where both cross-licensed each other allowing both companies to market worldwide [11], [12].

In offshore wind the NdFeB magnets are widely used offering a high remanent flux density and magnetic coercivity. NdFeB magnets are very attractive for the permanent magnet synchronous generators (PMSGs) as their usage enables high torque density and compact machine designs [13]. The PMSGs are available in both medium-speed and direct-drive configurations offering higher power density and efficiency and improved grid stability. Nevertheless, the PMSGs are not immune to faults and have their own challenges [14]. PMSGs can confront a local demagnetization and this refers to the loss of magnetic properties in particular areas of magnetic poles due to physical damage or localized overheating. Another type of PMSGs demagnetization is distributed in which a reduction of magnetic strength across the magnet occurs as a result of electrical faults or extensive exposure to high temperatures. The demagnetization problems of PMSGs are exacerbated in the harsh offshore environments where the thermal management is even more difficult due to excessive humidity, maintenance, and accessibility matters [14].

B. Dysprosium and Neodymium in NdFeB magnet

Neodymium and Dysprosium are important rare earth materials (REM) in the NdFeB permanent magnets employed in wind turbines and electric vehicles motors. Thus, the prices of Neodymium and Dysprosium are scrutinized. Since 2011, the prices for Neodymium fluctuated between 50 USD/kg to 280 USD/kg, with the highest price in 2022, during the Covid pandemic. Current prices are above 80 until 90 USD/kg. About the prices of Dysprosium, it appears that Dysprosium has much higher volatility than Neodymium as the prices fluctuated from a very low price of 28.50 USD/kg (in 2003) to a very high of 3,410 USD/kg (in 2011); currently, the prices are passing 500 USD/kg [3].

Dysprosium and/or Terbium are considered to be critical elements for the NdFeB magnets. The reason behind is that these two heavy REEs allow the permanent magnets to maintain their performance at high operating temperatures. In the early generation of the NdFeB magnet, 30 % of REE contained in the NdFeB magnet was represented by Dysprosium and Terbium (DyTb) known as heavy REE (HREE), and the rest – 70 % – was represented by the light REE (LREE) - Neodymium and Praseodymium (NdPr). However, this ratio of 70:30 of NdPr (LREE):DyTb (HREE) in the NdFeB magnets has brought a challenging situation as in the natural ores, the natural supply ratio of these LREE:HREE is near 98:02. This means that the Dy and Tb in natural ores are in much lower ratio than their usage ratio in the magnetic alloy. Dysprosium and Terbium are therefore more critical by having more difficulties in their supply chain with much higher prices. Thus, over the last decades, technological innovation such as the grain boundary diffusion technology contributed to reduce the percentage of DyTb in the Neodymium magnets to around 4 %. Nevertheless, DyTb are more critical than NdPr in their supply ratio comparative with their ratio in the modern NdFeB magnets [7]. In such critical context, further technological developments for the NdFeB magnets are recommended as the DyTb content is indicated to drop to around 2 % of the total REE contained in NdFeB magnets in order to match their law natural abundance in ore and the low supply ratio. This can be achieved through innovative technologies by adding Dy to the NdFeB magnets shape only where it is needed, rather than dispersed throughout the NdFeB magnet [7].

III. DISCUSSIONS

A. Reduction/substitution of REE and permanent magnets

Hybrid drives with smaller permanent magnets, magnet without REE, alternative technologies to lower cost and waste, and improved materials utilization are among the ways towards for substitution and reduction of REE [3]. The race in reduction and substitution of REE seems to have pushed the boundaries. An example is offered in 2024 by a deep-technology company which announced discovery of a new rare-earth-free permanent magnet with the help of its AI platform. This AI platform seems to be very performant as within just 3 months was able to discover new rare-earth-free magnet at 200 times faster than the speed of manpower [15]. It is worth to notice that currently there are no direct substitutes for the REEs in permanent magnets which could offer similar or better performance characteristics as the REE magnets offer. This draws attention that the substitutions need to be carefully chosen in order to minimize the impact on quality/performance [3].

The world's first high-performance rare-earth-free magnets capable of automotive-grade power or what is called "Clean Earth magnet" has been developed by the Niron Magnetics, a company which received the support and funding from companies such as Volvo Cars Tech Fund and General Motors [15]. This kind of magnet uses a mix of abundantly available Iron and Nitrogen, and was subject to research and development over a decade. However, further work is required in order to make such type of magnet ready for industrial scale production, like for offshore wind [15].

Other initiatives aimed to set the circular economy targets for permanent magnets. One of these initiatives on permanent magnet recycling is conducted by Vattenfall which ambitiously targets to achieve a 100 % circular outflow of permanent magnets from its decommissioned wind farms [9]

Recent versions of wind turbines models at Vestas do not employ heavy rare earth materials (HREE), also use significantly less light rare-earth materials (LREE) per MW [8]. Moreover, Vestas has opted for the gearbox technology while Siemens Gamesa has primarily committed to the direct drive option for offshore wind. The EU funded MADE4WIND project [16] is working on a promising solution of medium-speed geared drivetrains for large offshore wind turbines. The medium-speed concept can enable a more compact generator, with weight decreasing as the gear ratio increases. The project aims to design an optimized drivetrain to meet goals such as elimination of heavy rare earth elements (HREE) in the permanent magnets, achievement of high efficiency, maintaining high power density while operating at medium speed [16].

Another initiative which targets to reduce the REEs in the floating offshore wind is the INSPIRE project – an EU co-fund project recognized by the UN Decade of Ocean Science for Sustainable Development 2021-2030 as an UN Ocean Decade Endorsed Action. The INSPIRE project goes beyond the state of the art by integrating the on- and off-grid wind farms together with the hydrogen production in order to optimise the design, to reduce REE usage, to optimize the electrolyser lifetime, and to enhance the system lifetime [17], [18].

The European Raw Materials Alliance (ERMA) [19] has also brought to attention that a huge innovation potential is linked to the resource and cost efficient design of magnetic materials and motors. Furthermore, the ERMA Cluster Rare Earth Magnets and Motors [20] has developed an Action Plan with four main key recommendations: to address the European policymakers asking to be more active in REEs reduction; to encourage the original equipment manufacturers (OEM)s to buy significant percentage share of REM from the European producers; the products containing REEs and reaching to end of their life to be subject to regulations and standards which require them to be reprocessed and recycled in Europe; the required necessity for large private investments and state aid in the emerging European REE value chain [20].

B. Permanent magnets and sources of risk

The production of REEs is among the least diversified of all key energy transition minerals. The geographical concentration of REEs can be comparable with the cobalt and graphite in terms of mining. In 2023, the top three producers in the world account for 86 % of which China solely accounted for the 62 % of the global mined production. According to the IEA, the REEs have the highest geographical concentration for refining among all energy transition minerals, see Fig. 4 [4], in Appendix. It can be observed also that China alone represents 92 % of the REEs global refined output and has a global dominance [4]. In 2024, over 90 % of NdFeB magnets came from China. As a note, the supply chain for the REEs permanent magnets is highly concentrated in China, but the worldwide leader of the patent activity linked to permanent magnets is Japan [7].

The high geographical concentration of REEs in terms of extraction, processing and REEs magnets poses high risks of supply constraints and price volatility in case of geopolitical events. The growing demands of energy transition, key manufacturing industries needs and the rapid demand growth from technology, including clean energy technology, can also contribute to increase the economical and geopolitical risk [21].

It is worth to bring to attention that REEs and REE magnets are also linked with serious concerns about environmental damages. Extraction and processing of the REE materials necessary for energy transition technologies requires mining and processing with significant environmental consequences. The heavy sands such as monazite sands contain not only REEs, but also radioactive elements such as uranium and thorium. As an example, the production of one kilogram of rare earth oxides can produce almost one kilobecquerel of uranium-235 (U-235) equivalent of radioactive elements. The wastage containing radioactive materials from the REE refining and processing can spread to environment. As an alarming matter, only 17 % of the operating REE mines are in alignment with the Global Industry Standard on Tailings Management (GISTM) [4]. Outside of China, very few countries have the infrastructure and willingness to develop solutions for the storage of radioactive wastage by-products from the REE mining and refining [4]. There are critical stances which bring to attention the matter that the Western nations and European countries displace entirely blames on China for the heavy and long term environmental impacts of the REE mining, refining and manufacturing while maintaining a hypocritical position. This heavily suggests a “Not In My Backyard” approach where the developed regions and countries seek to benefit from energy transition technologies while avoiding the environmental burden of the mining/refining operations. Moreover, they depend on REE for technology development, and effectively have outsourced these “very dirty” and high risk industrial processes far away to other regions around the world.

It is undeniable the REEs and REE magnets have the capacity to undermine economic stability and global security, and to bring geopolitical tensions. The recent US tariffs were answered by China with the placement of export restrictions on REE, both mined minerals and permanent magnets. The export controls cover all countries, not only US, and exporters are required to obtain licenses for a particular list of REE which includes their oxides, alloys, compounds and mixture. The Chinese export control list announced at the beginning of April 2025 refers to the REE such as samarium, gadolinium, terbium, dysprosium, lutetium, scandium and yttrium. It can be noted that the HREEs such as Dysprosium is already covered by export control. This is an export restriction and not an export ban, but the Chinese exports of REE can decrease dramatically, and the prices can go high [22], [23].

The REEs have experienced two price major peaks: one in 2010–2011 which was linked to the Chinese decision to cut illegal mining and to restructure exports; and the second peak was registered in 2021–2022 during the Covid pandemic. Price volatility and market dynamics of the REE has created concerns about the investments in technology and manufacturing as companies have encountered difficulties in operations and profitability of business. Furthermore, users of materials and permanent magnets strives to cope with market changes and high prices [3].

According to the US and Japanese original inventors of the Neodymium magnet there are great difficulties in producing a “high-grade magnet without rare earths”. In order “to make a good high-performance magnet”, the REE are critical [12]. According to the Japanese inventor, a research project aimed to produce high-performance permanent magnet from iron-nickel compound was found unsuccessful. The US inventor from General Motors highlighted that the market of magnet is highly influenced by the REEs market. However, there are also other countries which have REEs resources such as the North America, Canada, India, and Australia. Therefore, the original Neodymium magnet inventors recommended “some political will has to be put forth to change the dynamics of the rare-earth market today”, and “Japan and Korea and Western Europe and North America will have to have some kind of government help to establish a rare-earth market outside of [China]” [12].

The pressure to substitute REE or other critical materials might be detrimental to the development of clean energy technology. Substitution indeed may be viable in the long term, but it will not solve the current and medium-term supply challenges [21]. The roadmap for the technology qualification, innovation and cost reduction in the floating offshore wind needs to incorporate challenges linked to usage of REE permanent magnets in offshore wind [24] . The ambitious targets for development of offshore wind need to take in account if the current supply chain will be able to provide REE permanent magnets according to the scale and cost required to support development of offshore wind.

In order to mitigate the risks which might evolve from the REE supply chain and REE permanent magnets providers, large wind turbine manufacturers has started to make efforts in order to build “sustainable and resilient supply chain for neodymium-praseodymium oxide”. An example is offered by the Siemens Gamesa which has secured a long term agreement with an Australian company, Arafura Rare Earths, in order to purchase several hundred tons of neodymium-praseodymium oxide annually [10].

In terms of production cost, the European Raw Materials

Alliance (ERMA) [20] has pointed out that the cost for production of REE magnets and motors is much higher in Europe than in China. According to estimations and taking in account different applications, there is a price difference of around 20–30 % for a magnet produced in Europe compared to its equivalent which is produced in China, depending on the application [25]. Over the decades, in China, the costs have been lowered by governmental support, direct and indirect subsidies and incentives, lower social, labour, and environmental standards, unilateral tax exemptions and other measures against competitors [20]. The ERMA emphasized that the original equipment manufacturers (OEM)s need to take urgent measures in order to diversify their REE supply chain, to support EU local suppliers, to enhance material knowledge for future motor designs and test facilities also to embrace a circular economy [20].

Among the risk mitigation strategies which need to be considered in medium term in order to reduce the REEs dependencies in Europe are the followings: development of a domestic supply chain, particularly, by taking in account the discovery of REEs ore deposits in the Nordic countries such as Sweden, Norway and Finland; development of mining, refining and manufacturing in EU; to diversify the REEs supply through international partnerships; to enhance the circularity of the value chain and increase the recycling of REEs and REE magnets; to support substitution and alternative solutions for REEs magnets [25].

IV. CONCLUDING REMARKS

Within the coming decades, the offshore wind is set for a major growth and the demand for permanent magnets and REEs is expected to rise dramatically towards 2030 and beyond. The permanent magnets are essential components of generators in wind turbines, either direct drive or hybrid. The REE magnets together with the REEs, metals, and alloys are coming mainly from China. While the supply chain for permanent magnets is highly concentrated in China, the patent activity linked to permanent magnets has Japan as the worldwide leader. Today, about 95 % of magnets are the REE magnets like the NdFeB magnets. This type of magnet uses REEs such as Dysprosium and Neodymium. The NdFeB magnets are seen to be the strongest magnets which are now available in the market. Within the wind turbine industry, the NdFeB magnets are widely used in offshore.

The sources of risk linked to the REE permanent magnets are discussed, but not limited to the followings: large increase in demand in the coming years, concentration of supply chain in particular geographical areas, energy security, market volatility and high prices, specialized workforce, constraints linked to patents, labour costs, role of national policies, international policies, concerns about the availability of critical resources, existing research and development and technology strengths. There are different type of risk which can be linked to sources of risk associated with the REE permanent magnets in offshore wind such as supply risk, economic risk, financial risk, technological risk, geopolitical risk.

There are different innovative technologies which targets to reduce or substitute REE and improve the cost of magnets without REE. Substitution in magnets can take place, for example, by replacing some elements with others or through kind of improvements in technological processes. An example is the reduction of HREE for a NdFeB magnet. Nevertheless, substitution of the NdFeB magnet with an alternative type of magnet and enhancing the performance of a low REE permanent magnets is not easy and presents different challenges and trade off in terms of costs and efficiency, and cannot offer similar performance characteristics as of today. At the system level, use of hybrid system can also contribute significantly to lighter generator and thus significant REE reduction.

V. ACKNOWLEDGEMENT

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APPENDIX

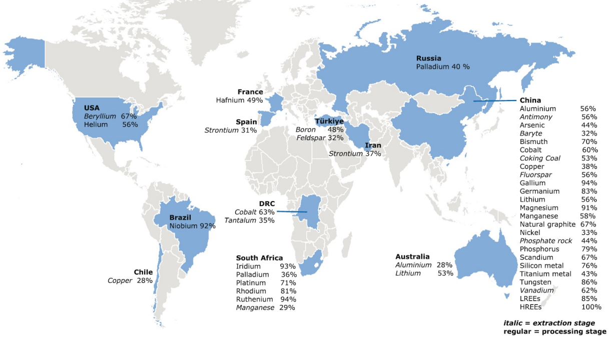

Fig. 3. World map of the main global producers accounting for largest share of global supply of CRMs (including REEs) in 2023 [6].

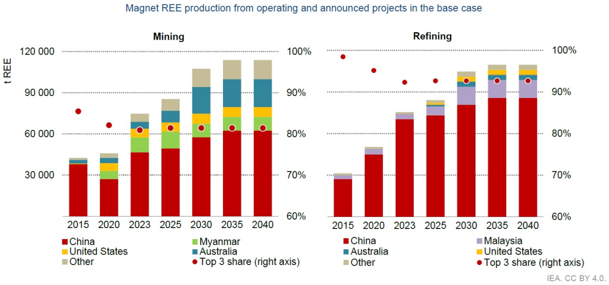

Fig. 4. Worldwide overview of the REEs mining and refining; REEs magnet [4].