Assessing the use of neodymium alloys in wind turbines from a Life Cycle Assessment perspective: a literature review

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Abstract

Direct drive permanent magnet generators are the most powerful and reliable alternative for kinetic-to-electrical energy conversion in wind turbines. The magnetic rotor is made of a metallic alloy containing neodymium, dysprosium and praseodymium, three rare-earth elements. The 2010 price bubble of rare-earth oxides increased the notoriety of these materials, which came out to be very impacting on the environment of the producing countries. Nevertheless, the great performances related to the use of these materials result in an environmental trade-off between the production and use phase. To make clarity on the subject, we critically review the literature on Life Cycle Assessments of wind turbines including rare-earths in the material inventory.

1. Introduction

Wind power has been the most exploited renewable energy source in the last years: in 2005, wind energy accounted for only 6% of the total installed power capacity in Europe; in 2016, it was 16.7%, corresponding to 154 GW (Nghiem and Mbistrova, 2017). In the same year, wind power was the generation technology with the highest share of new installations in Europe, more than half of the total new energy capacity (12.5 GW vs. 24.5 GW; Nghiem and Mbistrova, 2017). The European wind power capacity is expected to double to 324 GW by 2030 (Nghiem and Pineda, 2017). Kinetic-to-electrical energy conversion is driven by wind turbines (WTs): aerodynamic blades exploit wind to provide torque to a central rotor. The rotation is transmitted (sometimes through a gearbox) to a generator, to convert it into electric power (Chen et al., 2009). In 2016, about 340,000 WTs were spinning all around the world, with more than 480 GW of total installed global capacity (GWEC Global Wind Energy Council, 2017).

1.1. Neodymium magnets in wind turbines

In the last decade, direct drive wind turbines have gained increasing importance compared to geared systems. Introduced in the market in 1991, direct drive generators had a rapid growth in the last years due to their reliability and low maintenance requirements (Ivanovski, 2011). The largest share of operation and maintenance costs for geared turbines is associated with the gearbox itself, which is the component with the major number of moving parts, featuring contacts and wearing due to friction. Direct drive turbines, gearless, avoid this risk of blocking and reduce wear. Energy companies well appreciate this feature, especially for off-shore applications, where human intervention is complicated and expensive. Direct drive turbines are also superior to geared ones in terms of energy yield, while geared turbines are cheaper, lighter, and smaller (Ivanovski, 2011).

The main part of direct drive generators is a magnetic rotor (5 to 10 m diameter, up to dozens of tonnes in weight). The rotor can be made up of permanent magnets (PMs) or electrically excited electromagnets. Between the two solutions, the PM generator is the most reliable and the one with the highest energy yield (Ivanovski, 2011; Polinder et al., 2006), making it the most suitable solution for high-cost, high-performance applications as offshore wind farms. PM rotors are made of $Nd_2Fe_{14}B$, an alloy which exploits the magnetic properties of neodymium (Nd). Commercial alloys are drugged with other elements, resulting in an average composition of 65% Fe, 25% Nd, 6% Pr, 2% Co, 1% B, 1% Dy (Gambogi, 2016). PMs are also used in geared turbines, but in negligible quantities.

e. Rare-earth elements

Neodymium, as well as Praseodymium (Pr) and Dysprosium (Dy), is a rare-earth element (REE). REEs include seventeen chemical elements in the periodic table, specifically the fifteen lanthanides, scandium, and yttrium. Used in several technological products, REEs have been the subject of hot debate after the price bubble occurred between 2010 and 2011 (Fernandez, 2017). China, world leader in REEs production with a market share greater than 85%, actuated a restrictive export policy during 2009-2012. This policy generated an exponential increase in market quotations of these elements. The visibility brought by economic constrictions put the whole REEs context under attention, highlighting some criticalities. The production of rare-earth oxides is a complex process: the very low concentration in ores results in very aggressive chemical treatments; in addition, ores may be contaminated by radioactive elements as thorium and uranium (Laurent, 2014). Campbell (2014) states that one of China's competitive advantages to impose its market leadership in REEs mining is most likely its willingness to accept the associated environmental damage over the years.

The European Commission labelled REEs as critical raw materials, extremely strategic for the manufacturing industry but with a very vulnerable supply chain (European Commission, 2010). Efforts have been made to reduce the use of REEs to mitigate their economic and environmental impacts (Alonso et al., 2012; Massati and Ruberti, 2013). As for WTs, studies have been done to reduce the use of REEs in turbines generators (Pavela et al., 2017). Moreover, important WTs manufacturing companies adopted strong policies to avoid the use of PMs generators (like Vestas, market leader in WTs production; Vestas, 2014). While the 2010-2011 REEs price bubble retreated after the reopening of China's market (2012), REEs' environmental issues are still at the centre of a hot debate, influencing scientific opinions and companies' production policies.

2. Scope of the research and methods

There is a clear trade-off between performances of PMs direct drive WTs and environmental impacts related with the use of neodymium alloys. Materials whose extraction causes serious toxic emissions allow the creation of high-performing generators to better take advantage of renewable energy sources. Structured methods to evaluate benefits and burdens of different alternatives are required to quantitatively assess the related environmental impacts, from the production stage, through the use phase to the final dismantling.

2.1. Environmental impact analysis of wind turbines

Life Cycle Assessment (LCA) is a methodology to evaluate the environmental impacts associated with a given product or process over its full life cycle. By mapping unit processes in the different production steps and assessing resource consumptions and environmental pressures associated to each of them, LCA provides a comprehensive assessment framework of the environmental burdens related to a product (ISO, 2006).

Many LCAs regarding WTs are available, comparing wind power generation with other energy sources or contrasting the environmental performances of different wind turbine types. Exhaustive literature reviews provide aggregated information and results (see e.g. Arvesen and Hertwich, 2012; Davidsson et al., 2012). Nevertheless, the role of neodymium in turbines' overall environmental impact has been poorly investigated. Concerns regarding the impacts associated with the use of neodymium PMs in wind turbines have risen years ago, but the problem has rarely been analysed quantitatively, trying to make a balance of the overall costs and benefits of this material.

f. Environmental impact analysis of rare-earth elements

After 2010, the growing awareness about the environmental burdens of REEs' exploitation encouraged the research community to try to quantitatively assess the impacts related to these elements. In many cases, LCA has been used because of its systematic approach and the transparency of the procedure. Literature reviews are available on this topic too (Kossakowska and Grzesik, 2017). These studies show that the environmental impacts related to REEs can vary dramatically in different extraction and refining contexts: Weng et al. (2016) estimated the Gross Energy Requirement (GER) and Global Warming Potential (GWP) of the mining, beneficiation and refining processes of REEs in 26 REEs mining facilities. For instance, the GWP of neodymium oxide production can vary between 1000 and more than 10,000 kgCO_{2eq} per tonne of oxide depending on the geological and mineralogical features of the deposit. Schreiber et al. (2016) compared the environmental impacts of neodymium extraction from a new plant to be realized in Sweden with the Bayan Obo process (Bayan Obo is the biggest Chinese REEs deposit and with its facilities represents the world's biggest REEs production site). Better emissions control, as well as waste and sludge treatment forced by Swedish legislation, guarantees environmental impacts that are 60% lower for the Swedish process (11 midpoint impact categories analysed).

g. Research scope

This work reviews the studies that assessed the use of neodymium alloys for WT construction according to LCA standards. The study aims to shed light on the current knowledge on the topic, highlighting existing results and knowledge gaps, suggesting a research path to increase the scientific awareness about the environmental impacts and trade-offs of different WT generators. The final goal of the study is to make clarity about the environmental impact that the use of REEs alloys have on the overall lifecycle of a WT, to understand how deeply this impact is related with the mining context of REEs and to highlight if it is possible to clearly identify a best solution between the exploitation or avoidance of neodymium PMs in WTs. In the end, the authors provide an overview on the opportunities to implement circular economy strategies to recover neodymium PMs from WTs and dilute their environmental impact over several life cycles.

h. Research methods

The study has been carried out by identifying existing scientific publications on LCA studies of WTs including the environmental impacts associated with the use of neodymium alloys. To this end, the Scopus engine has been used with the following research query: (TITLE-ABS-KEY (“wind turbine”) AND TITLE-ABS-KEY (lca) OR TITLE-ABS-KEY (“life cycle assessment”) AND ALL (“rare earths”) OR ALL (“neodymium”)).

3 Results

19 publications satisfied the query limitation. The oldest was from 2012. Some of them were not directly relevant: three are the literature reviews previously mentioned (Arvesen and Hertwich, 2012; Davidsson et al., 2012; Kossakowska and Grzesik, 2017). Two are conference proceedings in which WTs, LCA and REEs are considered separately. Five are studies specifically focusing on REEs and do not provide any quantitative information directly related to WTs (Graf et al., 2013; Harmsen et al., 2013; Haque et al., 2014; Schreiber et al., 2016; Weng et al., 2016).

Some studies investigate the production of neodymium alloys for wind industry applications. They do not provide final quantifications about the use of PMs and their contribution to determining the overall environmental impacts of WTs, but it seems good to mention them here because they can provide a valuable reference for future, broader studies. Wulf et al. (2017) developed a cradle-to-gate Life Cycle Sustainability Assessment (the combination of a LCA, a Life Cycle Costing and a Social Life Cycle Assessment) to compare the production of $Nd_2Fe_{14}B$ exploiting REEs from the three main commercial mining and refining alternatives: the already mentioned Chinese Bayan Obo, the Mount Weld chain (extraction in Australia, refining in Malaysia) and the Mountain Pass chain (extraction and refining in USA). The Chinese alternative was the worst in all environmental midpoint impact categories, worst in 14 out of 15 social midpoint impact categories and best in all the economic midpoint impact categories. Holger et al. (2017) developed a more detailed Social Life Cycle Assessment to compare the three above cited alternatives. Again, the Bayan

Obo production chain resulted to be the most impacting on the social conditions of stakeholders. Jin et al. (2016) developed a LCA to compare virgin (Chinese) and recycled (through a hybrid mechanical-chemical process) neodymium PMs: recycled PMs were 40% to 70% less impacting than virgin ones, depending on the specific midpoint impact category.

Bonou et al. (2016) analysed an eco-design framework (a tool to design or re-design products to improve their sustainability through their entire life cycle) and its alignment with LCA standards. Ortegon et al. (2013) compared different dismantling processes for WT components, without applying a full LCA approach. Kouloumpis et al. (2013) proposed a combination of LCA and an On Site Environmental Impact Assessment (focusing on local effects and impacts on the biosphere) to evaluate the burdens of a wind farm in the UK. The analysis was based on secondary data from the Ecoinvent database. Ji and Chen (2016) developed a LCA of a Chinese wind farm. In all these studies, REEs were only mentioned but were not the subject of specific analyses.

(Adibi et al., 2017) developed a new endpoint impact category (called Global Resource Indicator, GRI) to assess the resource depletion potential of a product from a broad perspective (including recyclability and supply risk of the material). The study applied this impact indicator to the case study of 3-MW WTs. Datasets of two different types of WTs were obtained from Crawford (2009), and complemented using a permanent magnet Life Cycle Inventory (Adibi, 2016). In this study, the quantity of REEs inside the turbines is declared (415 kg of Nd, 15 kg of Dy) and their environmental impacts are assessed with the LCA methodology. Results are interesting: REEs are shown to contribute for more than half of the total GRI of the turbine, making turbines containing REEs more impacting than those based on different materials. However, the use of PMs allows a much lower consumption of copper (more than one tonne less). A reason of the high GRI of REEs is that their recycling rate (the fraction of a material that is recyclable) is set to 10%.

Lloberas-Valls et al. (2015) carried out a LCA to compare the environmental impacts of a 15-MW PM direct drive generator and a 15-MW second-generation high-temperature superconductor direct drive generator (a new rising electromagnetic technology). The analysis had cradle-to-gate boundaries (i.e. it included only the production phase) and considered only the generator (not the whole turbine). Results indicate that REEs account for the majority of the Ozone Layer Depletion Potential (OLDP) and a non-negligible proportion of the Eutrophication Potential (EP), while they have minor impacts on other indicators. Despite the OLDP of the PM generator is more than twice that of the other generator type, a normalization analysis (based on the EU25+3 year 2000 CML ReCiPe method) showed that the OLDP is the less relevant impact category (magnitude 10^{-9}). With respect to the most relevant impact category, the non-Fossil Abiotic Resource Depletion Potential (magnitude 10^{-5}), the PM generator is less impacting than the superconductor generator.

4 Conclusions

This review points out a general lack and lateness (nothing before 2012) in structured studies on the environmental impacts of Nd alloys used in the production of WTs. The LCA methodology, a mature and standardized assessment framework, has rarely been applied to assess those impacts. Some hints to develop further studies may be to (i) extend the analysis to a wider number of turbines and generators; (ii) broaden system boundaries to embrace the whole cradle-to-grave horizon and to consider not only the generator but the whole turbine (or the entire wind farm); (iii) base LCA analyses on primary data on REEs production in different contexts, in order to underline the role of mining and refining processes on the overall environmental burdens of a WT.

The available studies highlight the impossibility to identify a best solution between the use or avoidance of REEs in WTs: direct drive PMs WTs are the more effective alternative for offshore applications. Nevertheless, REEs usage has a serious influence on the sustainability of this choice. The high impact that REEs have on the OLDP indicator is easily ascribable to the slags released in atmosphere during chemical processes in mining. Moreover, REEs emerge to be the most impacting materials on the GRI despite their low contribution to the total weight of the WT (less than a tonne over thousands of tonnes). Their scarcity and the complexity of the supply chain force REEs to be evaluated by this indicator as materials like silver or palladium. Energetic efficiency, toxic emissions and economic-politic complexity coexist without prevailing in this complex trade-off scenario. Nevertheless, in case the PMs can be recovered and reused in several product lifecycles, the impacts generated by their production would be spread and reduced, allowing the performance opportunities to triumph. Adibi et al. (2017) assumed a PM recycling rate of 10% (directly impacting on the GRI), while Lloberas-Valls et al. (2015) stopped their cradle-to-gate analysis to production.

To recover PMs and mitigate their environmental impact, a circular economy (CE) perspective would be advisable in order to keep these materials in the loop. CE is a cross-sectorial market paradigm aimed to implement a closed-loop product life cycle, restoring when possible the entire end-of-life product or its components, otherwise recycling its materials or recovering its embedded energy (McKinsey & Co., 2012). Neodymium PMs can be recycled: however, if alloys to be recycled have different compositions, the hydrometallurgical processes (similar to the ones used in extraction from ores) required to obtain single REE oxides suitable for reintroduction into market are very impacting in consumption of chemicals and wastewater generation (Binnemans et al., 2013). If recycling is applied to alloys with the same composition (as those used in WTs of a same production company), the closed-loop recycling process based on hydrogen decrepitation requires less energy and no waste is generated (Binnemans et al., 2013). Recycling is not the only way to recover PMs: with a modular design-for-remanufacturing of rotors, PMs composed by unit-cell magnets with standard shape and size can be demagnetized, refurbished and re-magnetized as new PMs for new wind turbines. Direct reuse provides a dramatically lower environmental footprint than production of virgin magnets or hydrometallurgical recycling (Hogberg et al., 2016). A conscious development of a manufacturer-centred circular economy approach can provide an effective way to take advantage of the benefits brought by PM direct drive turbines while avoiding dramatic consequences on the environment of REEs-producing countries. Manufacturers best know the composition of their own products and can design and implement effective dismantling, remanufacturing, and recycling routes for rotor magnets (as well as for other components). The reuse of the same material over several life cycles can provide multiple benefits: the decrease of the environmental footprint of REEs' extraction, the low energy consumption in material reprocessing (compared with production from virgin materials), and the strategic advantage of a short and safe supply chain are key elements making the CE approach an effective way to take full advantage of the embedded value of end-of-life WTs and decrease environmental impacts associated to the extraction of virgin REEs.

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