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Substitution strategies for reducing the use of rare earths in wind turbines

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ABSTRACT

Considering the growing rate of global wind power and overall benefits of the permanent magnet synchronous generator (PMSG) wind turbines, the future demand for high-performing NdFeB magnet and its constituent elements is likely to increase. Future deployment of wind power generation may be affected by potential disruptions in supply and price rises of critical rare earth elements. By evaluating the substitution options for the rare earths permanent magnet-based wind turbines at the material and component levels, this paper shows that substitution has a real potential to alleviate the pressure on the supply of rare earths in the wind industry. Rare earth-free turbines with good efficiency levels were already developed and could be further adopted. Alternatively, the future demand for rare earths, in particular for dysprosium, could be reduced by improving material efficiency. The future market share of rare earth-based wind turbines will most likely depend on the evolution of the price of rare earths and the techno-economic advantages of PMSG in comparison to alternative technologies that use no rare earths elements.

1. Introduction

The energy sector has a crucial role to play in addressing climate goals and the use of renewable energy is already expanding rapidly worldwide (IEA, 2015). In 2015, the world's renewables-based generation capacity registered around 1985 GW, exceeding that of coal (1950 GW), and the prospects are that installations will further increase (IEA, 2016). Hydropower and bioenergy are by far the largest source of renewable energy supply, and wind and solar PV have led recent growth in renewables-based capacity (IEA, 2016). Wind power is one of the most advanced renewable energy technologies. In 2016, the global cumulative wind installed capacity reached 487 GW (GWEC, 2017). The China, the EU and the USA are leaders in the installation of wind power, currently accounting together for 83% of global installed capacity, with another 6% located in India (GWEC, 2017).

The EU has long been the front runner in wind power. In 2016, wind energy produced about 300 TWh, representing 10.4% of the electricity consumption in the EU through the cumulative installed capacity of 153.7 GW (of which 12.6 GW is offshore) (Wind Europe, 2017).

The 2050 roadmap developed by the International Energy Agency (IEA) implies intermediate stages of annual installed wind power global capacity, i.e. from 25 GW in 2012 and 63 GW in 2015 to 65 GW by 2020, to 90 GW by 2030 and to 104 GW by 2050 (IEA, 2013). Achieving these targets would also require an undistorted access to material resources, including rare earth elements (REEs). For example, neodymium (Nd), praseodymium (Pr), dysprosium (Dy) and terbium (Tb) are key elements in the composition of the NdFeB permanent magnet used in the latest generation of wind power technology, for example in permanent magnet synchronous generator (PMSG). According to our estimations about 23% of the global installed capacity in 2015 is based on wind turbines using the PMSG technology (Blagoeva et al., 2016). The remaining 77% are using conventional electromagnets generators based on magnetic steel and copper windings, both of them posing no issues about the security of material supply.

In the past few years, concerns about the supplies of certain raw materials, defined as '*critical materials*', which may not be sufficient to meet the growing demand due to the rapid deployment of low-carbon energy technologies have increased considerably. These fears were amplified after the rare earths 'crunch' in 2011 when near-monopolistic China imposed export restrictions on various materials. A number of studies assessed the risks associated with the supply of certain raw materials and analysed the impact of potential disruptions in supply on different economic sectors at corporate, country and region levels (CIT, 2011; Duclos et al., 2010; EC, 2014; UKERC, 2014; USDOE, 2011a; WWF, 2014; Zhang et al., 2017). The supply challenges of critical materials are often linked with the lack of production diversity, market

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complexities, price variability of the by-products (Nieto and Zhang, 2013) and geopolitical risk. An additional important factor that could impact the availability and supply chain of rare earth elements derives from the stringent environmental policy as the mining and refining are associated with water and soil contamination, human health, air pollution, etc.

The important role of material resources, in particular of REEs, in the wide deployment of emerging renewable energy technologies has been largely discussed in the literature (Baldi et al., 2014; Golev et al., 2014; Habib and Wenzel, 2014; Rollat et al., 2016). In recent studies conducted at the Joint Research Centre (JRC), we concluded that in the medium to long term, several low-carbon energy technologies could be at risk due to potential bottlenecks in the supply chain of certain raw materials (Moss et al., 2011, 2013a, 2013b). Among these technologies, wind energy is of particular concern because of its dependence on the critical rare earths – Nd, Pr, Dy and Tb – used in permanent magnets for the production of high-performing generators.

To address the issue of supply risks to critical raw materials, industry and governments are considering different mitigation strategies such as reuse, recycling, substitution, increased mine production and by-product extraction. However, many of these strategies are being thwarted by developmental, financial, regulatory and political aspects which, in the short term, make the implementation of any solution extremely difficult. The substitution of critical raw materials has received much attention and appears to play an important role, in particular, in cases where a new system/component is the substitute (Smith and Eggert, 2016).

Concise information about the substitution potential of rare earths in permanent magnets used in the wind power sector is rather scarce if not completely absent in the literature. This paper aims to fill this gap by evaluating up-to-date substitution possibilities of rare earths in wind turbines and analysing the potential impact of substitution on short-term demand for rare earths in the wind sector. Since in most cases an effective one-by-one material substitution with other less-critical materials appears to be either inadequate or non-existent (Gkanas et al., 2015; Graedel et al., 2015), in this paper we take into consideration also the reduction of rare earths amount achieved by increasing material efficiency as well as indirect substitution by replacing the entire component (e.g. wind generator) with other rare earth-free components.

2. Sources and approach

The research was carried out during 2015–2016 and it is based on an established methodology (Pavel et al., 2017). The assessment was based on our expertise in critical materials in low-carbon energy technologies and comprises an extensive literature review and expert engagement followed by synthesis and analysis of the results. Information was collected from published and grey literature, reports on critical raw materials, industry publications, and by engagement with relevant experts from academia, industry and NGOs who, in most cases, asked to remain anonymous. The key findings were discussed in a dedicated workshop with the participation of experts and stakeholders. They validated the outcome of the study, in particular the potential for using non-critical materials and alternative generators in wind turbines. Different technological aspects were addressed in relation to substitution of rare earth elements in wind turbines such as: performance, design and characteristics of substitutions, market trends, current and future status of R & D, technological advantages and disadvantages, technological restrictions, etc. (Table 1).

The feasibility of adoption of a material or component substitute was qualitatively assessed through the so-called '*technological development status*', which takes into consideration two principal components: technical performance and economic parameter (Fig. 1).

This approach for qualifying the substitution feasibility was already applied by our group in the context of substitution of critical raw materials in lighting applications (Pavel et al., 2016). Two main categories were differentiated in the case of wind turbines, i.e. technologies that are widely used or are in serial operation (marked in green boxes in the substitution map) and those which are in an earlier R & D stage (coloured grey). Moreover, each substitution path indicates which rare earths are either completely or partially substituted. The potential for substitution to reduce the short-term demand for rare earths in wind turbines was assessed through different scenarios, defined based on inputs from expert judgement and literature data. Making precise predictions about the penetration of substitution and future demand for rare earths in the wind power sector remains difficult due to a large number of parameters and uncertainty regarding economic developments, technology trends, markets, etc. In this paper, the values are designed to illustrate the future potential trends and impact of impact of substitution on the demand for rare earth-based permanent magnets in the wind sector.

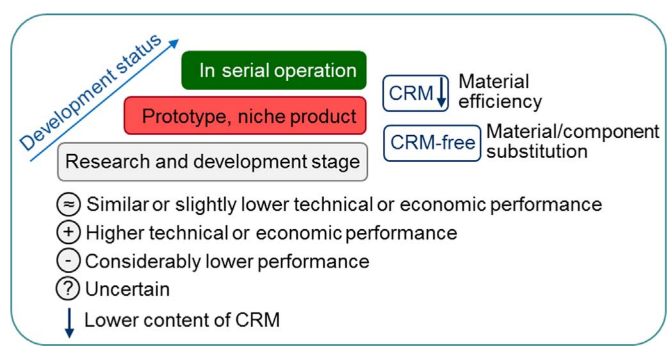

Fig. 1. Parameters used in the assessment of the substitution feasibility.

Table 1
Technological aspects, methods and sources addressed in the study of substitution for rare earth elements in wind turbines.

Technological aspect	Type of method	Source used for method
Current trends in research and development for substitutes in wind turbines with similar performance	Literature and systematic review; expert judgement	Public data reports and databases of peer-reviewed literature
Current performance characteristics of substitute materials	Literature overview and system analysis	Public data sources and peer-reviewed literature
Alternative system design (based on non-critical materials or critical materials at reduced quantities) that can deliver similar performance in wind power sector	System analysis and expert judgement	Results from previous studies linking raw materials to products
Innovative concepts of research, which may lead to substitution in the longer term	Desk research and system analysis	Public data sources and patent applications
Efficiency losses: how significant are they?	Expert judgement and desk research	Experts from the network of JRC and Oeko-Institute
Technological restrictions of substitutes in the different application fields	System analysis and expert judgement	Previous JRC studies. Interview with industry experts
Advantages/disadvantages regarding environmental aspects (e.g. hazardous substances, energy efficiency, recycling feasibilities of the end-of-life product)	Desk research and system analysis	Public data sources

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