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Dysprosium, the balance problem, and wind power technology

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HIGHLIGHTS

- We investigate the impacts of the increasing market share of wind power on the demand and supply of REE.
- The analysis is carried out using a dynamic material flow and stock model and three scenarios for Dy supply.
- The supply of Dy from all deposits will likely lead to an oversupply of the total REEs, Nd, La, Ce and Y.
- The supply of Dy from critical REE or Dy rich deposits will likely lead to an oversupply of Ce and Y only.
- Large quantities of thorium will be co-produced as a result of Dy demand that needs to be managed carefully.

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ABSTRACT

Wind power technology is one of the cleanest electricity generation technologies that are expected to have a substantial share in the future electricity mix. Nonetheless, the expected increase in the market share of wind technology has led to an increasing concern of the availability, production capacity and geographical concentration of the metals required for the technology, especially the rear earth elements (REE) neodymium (Nd) and the far less abundant dysprosium (Dy), and the impacts associated with their production. Moreover, Nd and Dy are coproduced with other rare earth metals mainly from iron, titanium, zirconium, and thorium deposits. Consequently, an increase in the demand for Nd and Dy in wind power technology and in their traditional applications may lead to an increase in the production of the host metals and other companion REE, with possible implications on their supply and demand. In this regard, we have used a dynamic material flow and stock model to study the impacts of the increasing demand for Nd and Dy on the supply and demand of the host metals and other companion REE. In one scenario, when the supply of Dy is covered by all current and expected producing deposits, the increase in the demand for Dy leads to an oversupply of 255 Gg of total REE and an oversupply of the coproduced REE Nd, La, Ce and Y. In the second and third scenarios, however, when the supply of Dy is covered by critical REE rich deposits or Dy rich deposits, the increase in Dy demand results in an oversupply of Ce and Y only, while the demand for Nd and La exceeds their supply. In the case of an oversupply of REEs, the environmental impacts associated with the REEs production should be allocated to Dy and consequently to the technologies that utilize the metal. The results also show that very large quantities of thorium will be co-produced as a result of the demand for Dy. The thorium would need to be carefully disposed of, or significant thorium applications would need to be found.

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1. Introduction

Wind power is one of the cleanest and fast growing electricity generation technologies. Between 1996 and 2012, the global annual installed wind power capacity increased from 1.3 GW to 45 GW, with annual market growth of 10% [1]. The global cumulative wind power installed capacity increased from 6.1 GW to 282 GW in the same period, with cumulative capacity growth of 19% [1]. Wind power technology has a significantly lower carbon footprint than fossil based electricity generation technologies with or without CCS, has a comparable or lower carbon footprint compared to other non-fossil electricity generation technologies, and has good overall environmental performance compared to other technologies [2,3]. Moreover, offshore wind technology has a lower carbon footprint than onshore technology [3]. In terms of the necessary resources, however, there is an increasing concern related to the availability of Nd and Dy.

The increasing use of wind power technology and its potential in future electricity generation have stimulated a number of studies evaluating the technology in terms of capacity factor, installation and maintenance cost, environmental impacts, and

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the availability of resources mainly the neodymium (Nd) and dysprosium (Dy) required for direct drive wind turbines [4–17]. In addition, a number of studies have recently evaluated the criticality of metals in terms of supply risk, environmental implications, and vulnerability to supply restriction [18–20] including the metals required for wind and other energy generation technologies [21–25].

Although recent studies provide useful information on the magnitude of the shortage of resources actually used in wind power technologies under specific scenarios, we argue that the impacts of the increasing market share of these technologies are not limited to the metals that are actually utilized but also to other metals co-produced with them. Co-production is the production of two or more metals from the same ore deposit, the element with high concentration being referred to as the "host" metal and those with low concentrations as "companions". The complexities related to co-production might result from either the demand for the host metals or for the companion metals [26]. Examples of co-production concerns are given by Maxson et al. [27], Elshkaki and Van der Voet [28] and Elshkaki and Graedel [29].

The Nd and Dy that are essential for the direct drive wind turbines are co-produced with other rare earth elements (REE), mainly from iron, titanium, zirconium, and thorium deposits. To increase the production of Dy and Nd it is necessary to increase their rate of recycling, to increase their recovery rate from ores, or to increase the production of the host metals. However, increasing the extraction of the host metals to satisfy the demand for Dy and Nd will result in an increase in the production of other REE and other companion metals. This is the balance problem, which is the balance between the demand and the natural presence of the REE in ores [30,31]. The possibility of the oversupply of some of the REE and the shortage of others has been indicated in several studies [32–36]. In this paper we discuss the impacts of increasing Dy and Nd production from primary resources in order to meet their future demand on the supply and demand of their host metals and other companion REE.

1.1. Background on rare earth elements

The rare earth elements (REE) are a group of 15 lanthanides: lanthanum (La), cerium (Ce), neodymium (Nd), Praseodymium (Pr), samarium (Sm), europium (Eu), and gadolinium (Gd) are classified as light rare earth elements (LREE), and terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu) as heavy rare earth elements (HREE). Promethium (Pm) is also a lanthanide element, but because all its isotopes have short half lives it is no longer present in rare earth deposits. The elements scandium (Sc) and yttrium (Y) have properties similar to the lanthanides and are usually included in the list of REE. Some of these metals are currently used in large quantities (La, Ce, Nd) and others in small quantities in applications that include magnets, phosphors, ceramics, catalysts, batteries, glass polishing and additives, and automobiles.

Despite their designation, total REE abundance is more than that of silver, nickel, copper or zinc, and the abundance of several of the individual REE is similar to or larger than many better known industrial metals [37]. REE are currently produced in small number of countries, of which China is the largest producer with 96% of the total world production in 2011. Other countries, including Russia, Australia, India, and Brazil, produce the remaining 4% [38].

REE deposits can be found in a large number of countries, and several new projects are being developed in Australia, Canada, USA, South Africa, and Greenland. Fig. 1 shows the share of several deposits in the current and expected production of rare earth oxides (REO) from which REE are produced [13,34,39]. Some of the new projects are expected to start production in 2014 and others from 2015 onwards. Some deposits are rich in LREE and others in HREE. Fig. 2 shows the share of individual REE in current and expected producing deposits [37,40–45].

The production of REE in Mountain Pass in California and Mount Weld in Australia was exclusive for REE but the production in China, Russia, Canada, Brazil, and other deposits in Australia was as a co-product of iron, titanium, uranium, zirconium and thorium respectively [33].

Dy is a HREE that is co-produced in small quantities from only a few deposits. However, its demand in magnets is expected to increase significantly in the future [4,7,13,46]. Although there are increasing efforts to reduce the amount of Dy in the magnet while maintaining performance, the improvements are unlikely to affect metal demand in the near future [47–49]. This has lead to identify Dy as one of the most critical metals (au Department Of Energy. Critical Materials Strategy. Washington (DC) [21]).

2. Methodology

2.1. Scenarios for the future electricity generation technologies

Several scenarios have been developed recently to analyze possible futures of the energy system in general and of specific renewable technologies in particular [50–55]. Some of these scenarios assume a world with no major changes, while others assume a world with moderate or major changes under a vision that policy options in favor of renewable energy will be selected. In this regard, the United Nations Environmental Programme (UNEP) as part of its third Global Environmental Outlook (GEO-3) developed a set of four scenarios, one is a world in which market-driven developments converge on the values and expectations that prevail in industrialized countries (Market First); another a world in which strong actions are undertaken by governments in an attempt to reach specific social and environmental goals (Policy First); a third a world of great disparities where inequality and conflict prevail, brought about by socio-economic and environmental stresses (Security First); and finally a world in which a new development paradigm emerges in response to the challenge of sustainability, supported by new, more equitable values and institutions (Sustainability First) [55]. In the present analysis, the total electricity demand and wind power market share is based on the renewable energy friendly "Policy First" scenario [56] combined with details from the Revolution scenario of the European Renewable Energy Council and Greenpeace [57].

2.2. Description of wind power technologies

Wind turbines can be installed either on land or offshore. Although offshore wind currently represents less than 2% of the global wind power installed capacity, the market share of offshore technology is expected to reach 20% by 2020 and 40% by 2030 [50]. In our work, the future offshore wind market share is assumed to be similar to those given by EWEA [50], with a maximum market share of 50% by 2050. It is also assumed that direct drive (Nd and Dy – containing) generators will be mainly used for offshore wind turbines.

The electricity output of wind power farms is determined by the number of installed turbines, the rated power of the turbines, and the turbine capacity factor (CF), which is function of the wind speed at hub height, the turbine diameter, losses due to the presence of wakes from individual turbines, down time for maintenance, electrical losses within the wind farm, and other losses. Three scenarios are used for the future CF of wind power plants in Europe, US and China, and the rest of the world, based on infor-

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