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Special Report

CRITICAL RAW MATERIALS IN WIND POWER EXPANSION

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Introduction

The expansion of renewable energies is increasingly being discussed in terms of resource consumption as well as in terms of cost, security of supply, acceptance issues and effects on land utilization and landscape appearance. It is beyond dispute in the discussion that overall resource utilization of an energy system is generally considerably lower the more it is based upon renewable energy (and not aligned primarily towards biomass). This does not necessarily mean however that renewable energy can be seen as unproblematic with regards to deployment of resources. In particular, little investigation has been conducted into the consumption and long-term availability of mineral raw materials generally required to manufacture energy converters and infrastructure. A current study (Wuppertal Institute 2014) contributes towards closing this analysis gap, providing information on whether and how energy transition with a high level of renewable energy expansion can be structured more resource efficiently.

Analytical approach

Investigated as part of the study was which "critical" mineral raw materials will be relevant before 2050 in Germany for the manufacturing of technologies which generate power, heat and fuel from renewable energy. Long-term availability of raw materials identified, supply situation, recycling capability and environmental conditions of transportation are taken into account in the categorization of "critical". Initially included in the analysis were all technologies which could be deployed in Germany over coming decades, supplemented by infrastructure installations such as energy stores and power networks. Secondary applications such as batteries in electric vehicles which do not use renewable energy directly are not included.

The analysis was conducted in due consideration of different long-term energy scenarios created for the German energy system. They describe different paths of renewable energy expansion to 2050, shown in Figure 1 for the electricity sector. The long-term expansion requirement was identified for relevant technologies based upon these scenarios. For this, four possible expansion paths "low", "medium", "high" and "very

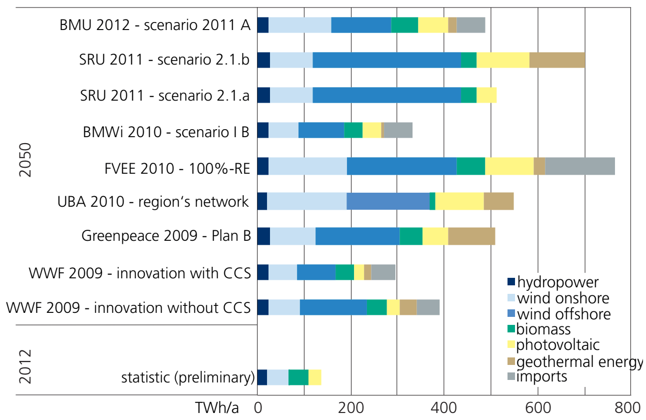

Figure 1: Power generation from renewable energies in Germany in 2050 according to various scenarios

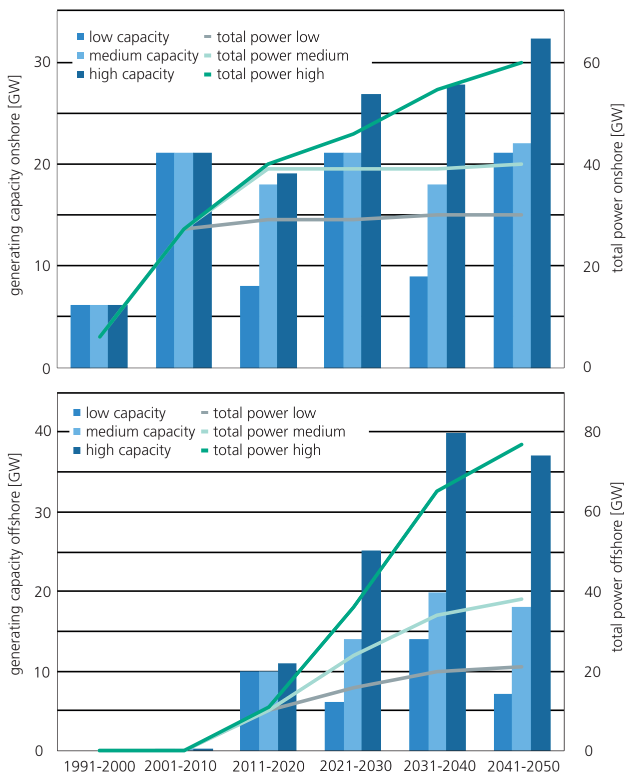

Figure 2: Overall capacity at the end of a decade and capacity expansion per decade for the different expansion paths

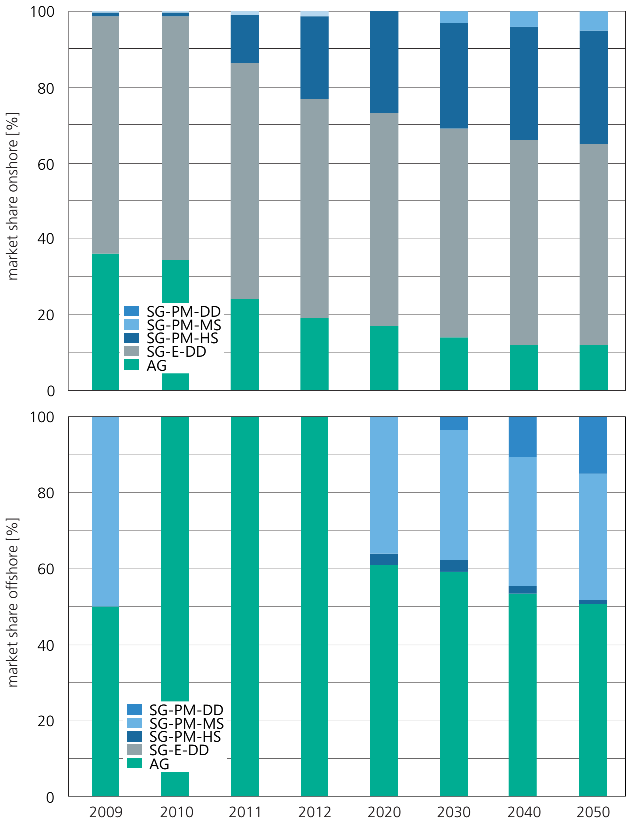

Figure 3: Technology market shares in "Continuity" scenario (onshore top, offshore bottom)

high" were derived for the period up to 2050, and the expansion required (including replacement infrastructure) between 2011 and 2050 was calculated for every path. This expansion is shown in Figure 2 for onshore and offshore wind power.

Furthermore, roadmaps including estimations of future market shares and potential technical development of different installation types were developed for the relevant technologies. Associating the expansion requirement with specific material consumptions over time enabled the cumulated quantities of mineral raw materials required to generate the required capacities until 2050 to be ascertained and assessed.

Analysis of wind power

Expansion path. Identified as potentially critical technologies with regards to the supply of mineral raw materials were individual components and sub-technologies of wind power. Neodymium (Nd) and dysprosium (Dy), being used more and more in generators with permanent magnets (PM), are critical minerals here. They make it possible to deploy more powerful and lightweight wind turbines. Cumulated expansion requirements for the low, medium, high and very high paths of 59, 79, 106 and 282 GW respectively (onshore), and 37, 62, 113 and 123 GW respectively (offshore) were derived for wind power for period 2011 to 2050.

Market development. Three roadmaps were developed for expansion across Germany to 2050 to estimate future technologies and their market shares. For the onshore wind market, they are based upon market development from 2009 to 2012. To determine this information, data from Fraunhofer IWES (Institute for Wind Energy and Energy System Technology) was analyzed by manufacturer and installation type, and categorized by wind turbine class (see Table 1). Offshore market shares were determined on the basis of all known offshore projects in the German North and Baltic Seas for which a construction permit has been issued as a minimum, or which are already in the planning or construction phase. The roadmaps are built upon three scenarios to include potential bandwidths from the development of technical and economic framework conditions for wind power.

In the "Continuity" scenario, the trend towards installations with increasingly higher nominal capacities is slowing, attributable perhaps to legally binding height restrictions. Following on from this is broad retention of the decentralized structure of onshore wind power usage. Given that the technical requirements of a wind turbine do not change to any great extent, manufacturers are subjected to comparably lower pressure to innovate, meaning low dynamics in any changing of market shares are assumed (Figure 3). Low pressure to innovate and a low level of dynamics in continued development are also assumed for the offshore sector. Also potentially contributing towards this development is that the goal stated, of more powerful and lightweight installations, cannot yet be met from a technical standpoint.

In the "Upscaling" scenario, the trend is intensifying towards large-scale, 10 MW class installations. This is because larger hub heights and rotor diameters mean specific material requirements and costs can be reduced significantly. The problem of high tower top weights is resulting in a change of technology direction - towards PM generators (Figure 4). Onshore will therefore continue on the trend observed since 2010. This change will be more intense for offshore, meaning asynchronous machines will have been broadly replaced by PM-based generators by 2050.

In the "HTS" scenario, significant usage of high-temperature superconductors (HTS) is assumed in addition (no figure). In terms of maturity for production and entry onto the market, HTS generators would be direct competitors to driveless SG-PM generators. Manufacturer market shares are therefore identical to those in the "Upscaling" scenario. Market shares of SG-PM-DD generators are reduced in the roadmap to make way for HTS generators with direct drive (HTS-DD) - to reach 12% and 17% market share for onshore and offshore respectively by 2050.

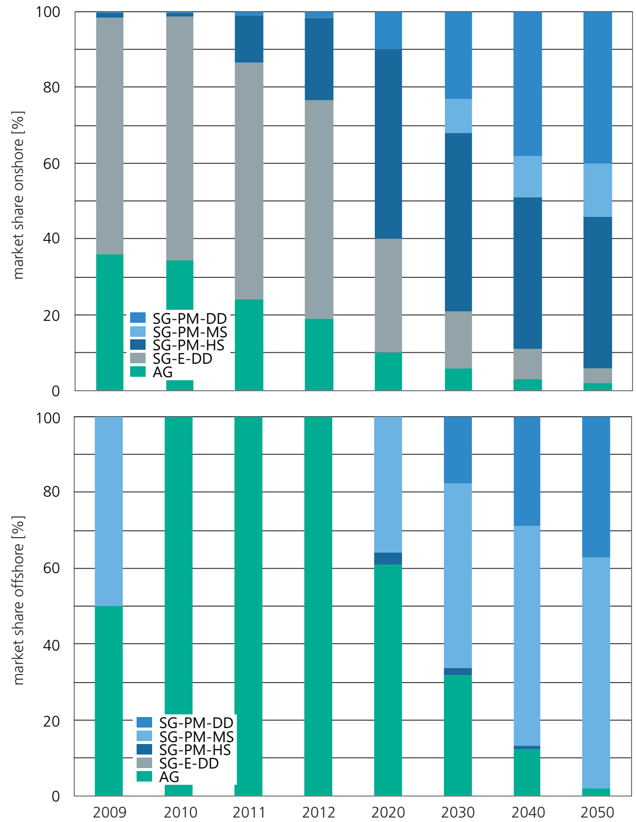

Figure 4: Technology market shares in "Upscaling" scenario (onshore top, offshore bottom)

Excitation	Generator type	Drive	Short-form	Resors	2014	2025	2050
Permanently excited (PM)	Synchronous (SG)	Direct drive	SG-PM-DD	Nd	201.5	162.5	130.0
				Dy	15.0	11.7	11.7
		Medium speed drive	SG-PM-MS	Nd	49.6	40.0	32.0
				Dy	3.7	2.9	2.9
		High speed drive	SG-PM-HS	Nd	24.8	20.0	16.0
				Dy	1.8	1.4	1.7
Elektrically excited (E)	Asynchronous (AG)	High speed drive	AG	–			
		Direct drive	SG-E-DD	–			
	Synchronous (SG)	High temperature - superconductor (HTS) with direct drive	HTS-DD	Yttrium	–	2.3	2.3

Table 1: Overview of generator types in the German installation mix

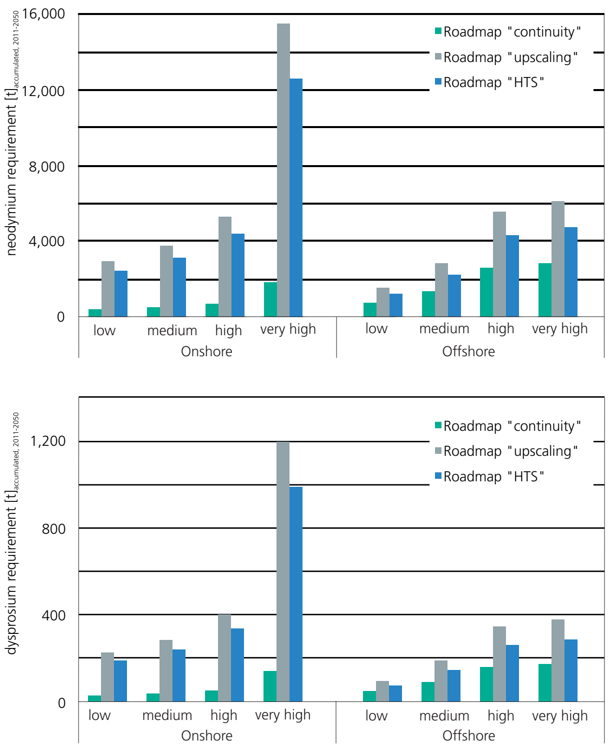

Figure 5: Cumulated neodymium (top) and dysprosium (bottom) requirement for new wind turbines installed in Germany between 2011 and 2050

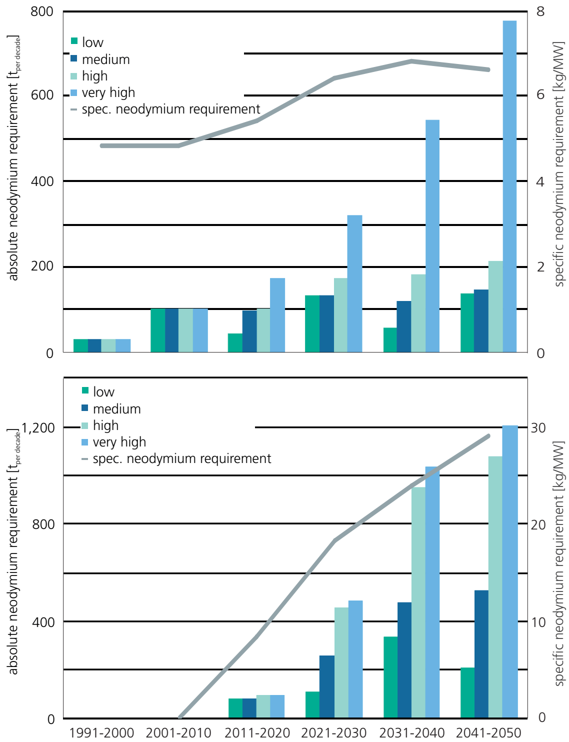

Figure 6: Neodymium requirement for new onshore (top) and offshore (bottom) wind turbines installed in Germany in the "Continuity" roadmap (specific and absolute, for each decade in each case)

Development of specific consumption of rare earths. Lanthanide series such as neodymium (Nd), dysprosium (Dy) and yttrium (Y) are amongst the group of rare earths. Rare earths are not rare (as their name would suggest) but do not, or only to a minimal extent, form deposits. Accordingly, they usually only occur in low concentrations and are primarily acquired as by-products. Nd and Dy are used in neodymium-iron-boron permanent magnets for synchronous generators in wind turbines. These "rare earth magnets" have the benefit of high magnetic energy density, meaning lower generator weights can be attained. Quantitatively, neodymium and praseodymium, which are very similar chemically and physically, dominate. Additives of dysprosium and terbium are also used in low quantities to raise the Curie temperature of these magnets. To determine the Nd/Dy requirement for PM magnets, their weights and specific requirements in today's wind turbines were estimated on the basis of literature analyses (Table 1). Values for years 2025 and 2050 were assumed on the basis of literature specifications and discussions with experts, whilst the field strength and density of a magnet, and so the specific magnet weight, were assumed as unchanged.

Cumulated consumption of neodymium and dysprosium. Figure 5 shows the cumulated requirement of Nd and Dy over the entire period in question. It can be seen clearly that the requirement for critical raw materials depends not only on the level of wind power expansion in the future, it also depends to an even greater extent in part on the technology mix to establish itself. This can be seen in particular for the requirement of Nd and Dy for onshore wind turbines. In the "Continuity" roadmap, there is only 12% to 13% of the Nd and Dy requirement needed over the entire observation period as compared to the "Upscaling" roadmap. For offshore wind power, the differences between the various roadmaps are not as great because in the "Continuity" roadmap the assumption is that "medium speed" and "direct drive" generator types having a particularly high requirement of critical raw materials will gain significant market share for new installations.

Figure 6 clearly illustrates that the average specific Nd requirement for onshore wind turbines in the "Continuity" roadmap will initially rise from 5 to 7 kg/MW between 2001 and 2040. It sinks again slightly to 6.4 kg/MW in the last decade. Whilst over the entire period in question efficiency improvements and substitution efforts mean average specific consumption values of all individual generator types (Table 1) fall, the assumed continued increase of the market share for generators with PM magnets, primarily "high speed", but also "medium speed", means the specific requirement of newly built wind turbines rises in all but the last decade. In the first offshore installations in Germany which came online in 2010, only asynchronous generators were fitted, meaning no Nd entered the balance for the first decade. Afterwards, the average specific requirement of installations newly-built every decade rises to just under 30 kg/MW, caused by the share of installations with PM magnets, mainly "medium speed" and "direct drive", increasing over time. In the "Upscaling" roadmap (not shown), the requirement due to considerable expansion of these installations taking place rises for onshore and offshore to just shy of 70 kg/MW.

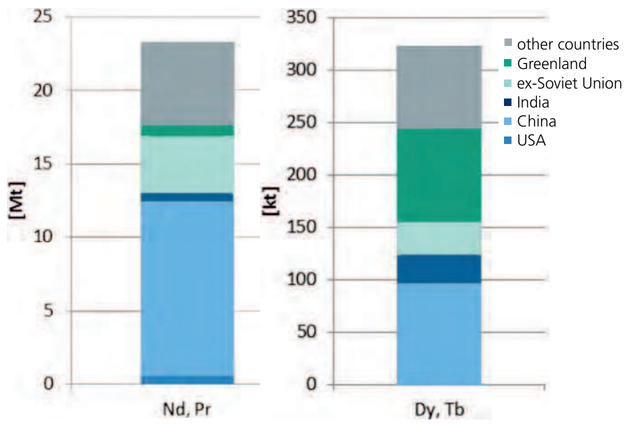

Figure 7: Distribution of reserves of neodymium (including praseodymium) and dysprosium (including terbium)

Assessment of resources

If geological availability was taken on its own, all scenarios and expansion paths looked at for wind power usage in Germany can be implemented, even if similar expansion of wind power is assumed for all other countries. Used here was a "budget approach" from climate policy, in which global reserves and resources are weighted using the percentaged population of Germany, and reduced by consumptions from other sectors.

On the other hand, adequate supply of the quantities required by Germany cannot necessarily be guaranteed. Firstly, excavation levels from mines are as low as 10% in part. Minerals theoretically available in sufficient quantities are therefore remaining unused or partly unused. Also, very different environmental performances must be factored into the extraction process. Mining Nd and Dy brings with it considerable environmental impact, depending on the minerals mined, the processing technologies and the addition of other materials to the minerals extracted. On the other hand, there is a high level of dependency on a few supplier nations, entailing a corresponding bearing on security of supply (see Figure 7). China is currently the only extraction nation of relevance, especially for Dy. At the moment it is unclear as to whether other supplier countries can establish themselves in the long term, and under what conditions extraction would take place (including transportation costs, quality of deposits and environmental legislation).

Alternatives. Despite the benefits of rare earth magnets, the risks associated with this dependency mean established and new technologies not using rare earths should continue to be developed and enhanced.

- For onshore installations, the use of Nd and Dy is not an absolute necessity because problems such as high tower top weight and cost-intensive maintenance work for turbines pertain mainly to offshore installations. At least the recent rapidly rising trend of also using onshore installations with PM magnets cannot be justified using the same requirements as for offshore installations. Non-critical, electrically excited generators could continue to be used for onshore, especially in the 1 to 3 MW class.

- Potentially usable for offshore installations in the long term are electrically excited synchronous generators in which HTS replaces in part the copper in the rotor coils, and so feature much lower generator weights and volumes than conventional direct driven synchronous generators.

If installations with PM magnets continue to be used however (in the offshore sector in particular), they should at least be designed so as to be recyclable. In terms of perspective, the development of a recycling system must be evaluated to get access to recycled Nd and Dy for the replacement requirement in 20 to 30 years. Still, there are engineering challenges in process technology for high-quality recycling that are yet to be addressed.

Conclusions

Overall the study makes clear that the geological availability of mineral raw materials essentially does not represent a restricting factor for the planned expansion of renewable energies in Germany. However, potential shortfalls in supply may mean that not every technology variant can be deployed without restriction. In addition to wind power, individual technologies of photovoltaics (thin film) and battery storage (Redox flow batteries based on vanadium) were identified as critical. However, for these technologies there are non-critical alternatives which could be used increasingly in the future or which are already dominant in the market. Geothermal energy could not be assessed due to a lack of data. All other technologies from the power, heat and transport sectors can most probably be regarded as non-critical for direct deployment of renewable energy. The general suggestion nevertheless in safeguarding the supply of raw materials for Germany is to place the medium-term focus on efficiency and recycling strategies. This way the increase in resource efficiency and recycling capability can take center stage in technology development. Existing recycling potential should also be leveraged. However, every recycling method is associated in part with considerable material losses and high energy usage. So in addition to recycling strategies, it is strategies for prolonging service lives in particular which should be developed in close collaboration with the industry.

Acknowledgement

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Literature

Wuppertal Institute (2014): KRESSE – Kritische mineralische Ressourcen und Stoffströme bei der Transformation des deutschen Energieversorgungssystems (Critical mineral resources and mass flows in the transformation of the German energy supply system). Final report to the federal ministry for economic affairs and energy (BMWi), with cooperation from Karin Arnold, Jonas Friege, Christine Krüger, Arjuna Nebel, Michael Ritthoff, Sascha Samadi, Ole Soukup, Jens Teubler, Peter Viebahn and Klaus Wiesen. http://wupperinst.org/de/projekte/details/wi/p/s/pd/38/. Wuppertal