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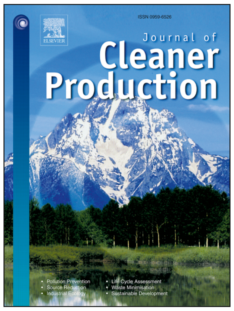

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A circular economy metric to determine sustainable resource use illustrated with neodymium for wind turbines

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Abstract

The finite capacity of the Earth to provide the resources needed to make products is beginning to dictate policy decisions and citizen behaviours. Herein a methodology is proposed that considers the function (i.e., efficiency and durability) of a product as a way of normalising and hence justifying its resource use. Titled 'Performance-weighted abiotic Resource Depletion' (PwRD), this approach allows the resource use of different products to be directly compared, analogous to an absolute sustainability assessment. The PwRD metric quantifies concerns over the supply risk of elements and indicates reasonable actions to sustain a circular economy. This new format of circularity indicator is explained with the case study of neodymium for wind turbine magnets. Individual products as well as larger infrastructure projects such as wind farms can be assessed. It was found that the electrical energy produced by a wind turbine in the USA does not justify the quantity of neodymium required. Demand for the function of products is a variable in PwRD and is equally important as resource use in sustaining a circular economy. In regions of low electricity demand per capita such as the Philippines and Pakistan, the same quantity of neodymium as used in a wind turbine installed in the USA was found to be acceptable for sustaining a circular economy.

Keywords

Sustainability; Circular economy; Wind turbine; Renewable energy; Neodymium.

1. Introduction

There is consensus amongst many governments, institutions, and citizens that together we must act to limit the impact of human activities on the ability of the Earth to sustain habitable living conditions. There are equally important policies dedicated to improving economic and social equality. All the above are brought together by the United Nations Sustainable Development Goals (United Nations, 2015). To achieve a sustainable society, alternative methods of energy harvesting and storage are required for climate change mitigation. This transition is creating a high demand for metals and other minerals (Sovacool et al., 2020). To take one example, neodymium flows into the European economy have increased from ~100 tonnes in 1990 to ~2000 tonnes/year to meet demand for NdFeB permanent magnets (Ciacci et al., 2019). It has been suggested that the future availability of neodymium could act as a bottleneck for the production of electric vehicles, wind turbines, and other low-carbon technologies (de Koning et al, 2018).

Monitoring and protecting the supply of critical raw materials is a priority of governments and industry (the supply risks of the elements are given in Supplementary Material Figure S1). Resources must be preserved and used responsibly to be able to sustain equitable environmental and societal conditions. This sentiment is embodied by the 'circular economy' concept and, while many definitions of a circular economy have been proposed (Kirchherr et al., 2017), the fundamental concept is to optimise the use of materials, thereby minimising resource depletion and waste (Velenturf and Purnell, 2021).

The link between circular economy and environmental sustainability is established at an institutional (Desing et al., 2020) and a global level (Hanumante et al., 2019). Conceptual frameworks aligning circular economy ideals to the fulfilment of societal needs are also being developed (Alaerts et al., 2019; Schroder et al., 2020). In order to evaluate the ‘circularity’ of individual products, several characteristics can be measured, e.g. recycled content and ease of disassembly (Mesa et al., 2018; Moraga et al., 2019). However, as Niero and Kalbar (2019) commented, “*no consensus has been reached yet on what [circular economy] indicators at [the] product level should measure*”. Attempts to introduce such a metric include ‘Longevity’, which is the lifespan of a product plus the working duration of the materials that is added by repair or remanufacturing (Franklin-Johnson et al., 2016). Another calculation has been proposed as the equivalent of recycled content but in monetary units instead of mass units (Linder et al., 2020). These approaches emphasise the necessity of reducing our reliance on virgin resources and maximising the functional lifespan of materials, but a means to compare different products on the same basis with a robust link to sustainability is yet to be established. The emissions or resource use associated with a product could be half that of a dissimilar product, but as their purposes are different, it could be that the impact of the more environmentally burdensome product is tolerable because its function is more valuable to society. A satisfactory evaluation of circularity that is applicable at different scales (product to infrastructure project to region) has also been elusive.

Absolute sustainability assessments have been developed to quantitatively determine if the environmental impact of an activity, e.g. tomato farming (Bjørn et al., 2020) or European clothes washing habits (Ryberg et al., 2018a) can be considered as sustainable. As shown in Figure 1a, the comparative benchmarking of life cycle assessment (LCA) is replaced with a comparison between the actual impact of an activity and the maximum permissible impact that could be sustained (the latter is known as the environmental carrying capacity, see Bjørn et al., 2016). The resulting values are unitless and represent a sustainable impact if less than or equal to 100%. Carrying capacities derived from Planetary Boundaries are known as the Share of the Safe Operating Space (SoSOS, see Ryberg et al., 2018b). The Planetary Boundaries quantify the limit of different Earth-systems before irreversible changes to climate and other aspects of the environment occur (Steffen et al., 2015). The SoSOS is allocated according to the scope of the assessment, usually by the economic value of an activity within a region (Hjalsted et al., 2021). Ryberg et al. (2018a) calculated that the environmental impacts of laundry in Europe are unsustainable with the exception of stratospheric ozone depletion, which depending on the allocation method to produce the SoSOS, is considered sustainable.

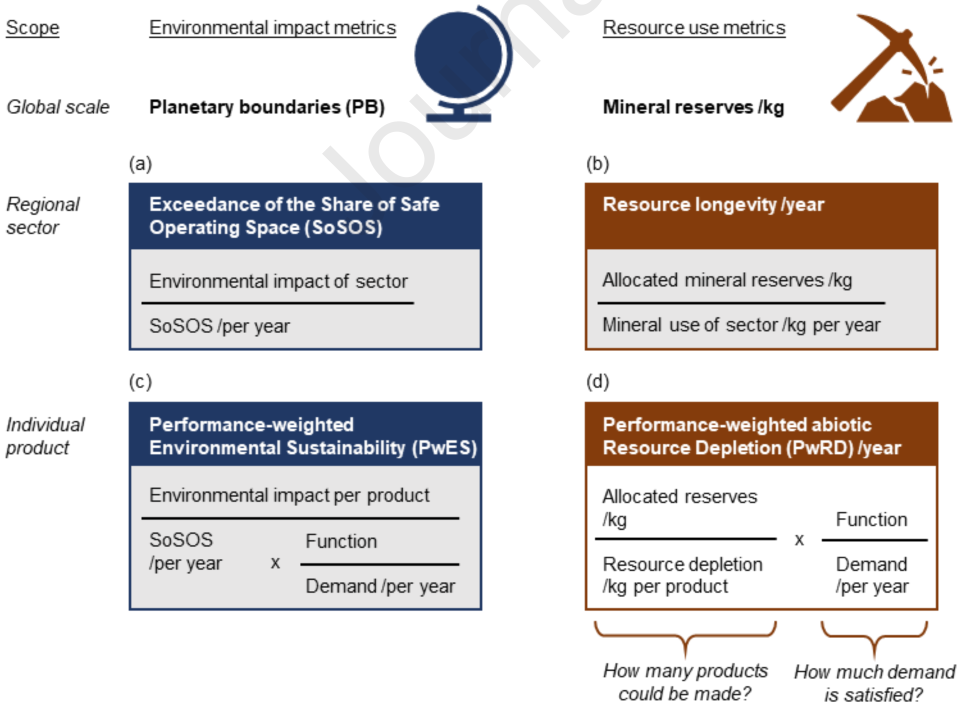


Figure 1. A comparison between absolute sustainability assessments. (a) Regional (environmental) absolute sustainability assessment. (b) The analogous regional sustainability assessment for abiotic depletion. (c) PwES, a product-level absolute sustainability assessment. (d) The format of the PwRD metric.

Planetary Boundaries describe environmental conditions but not the consumption of finite resources which are not regenerated on a short timescale. If the equivalent of a SoSOS is created for abiotic resources, this becomes the equation in Figure 1b. These absolute sustainability assessments can be scaled down into a product-level indicator with a weighting derived from the efficiency of a product. Performance-weighted Environmental Sustainability (PwES) applies this principle to environmental impacts with corresponding Planetary Boundaries in Figure 1c (Sherwood, 2021). Performance-weighted abiotic Resource Depletion (PwRD) is introduced in this work as a product-level sustainability assessment of resource use (Figure 1d), analogous to the inverse of PwES. If desired, the PwRD calculation can be repeated for all the different materials embodied in a product to establish the least sustainable components. Recycled materials are omitted from the PwRD calculation because the assessment evaluates the use of feedstocks that cause resource depletion.

There are several aspects to PwRD that differentiate it from a LCA mid-point indicator of abiotic depletion. A conventional LCA reports the impact(s) of a product based on a functional unit (e.g., vehicle emissions per kilometre). The magnitude of an impact does not tell us if it is sustainable, and the results are only comparable to other products whose function is described with the same functional unit. In PwRD, the resources required to manufacture a product and/or maintain its operation are normalised by the availability of mineral reserves. Resource depletion is now interpreted in the context of its severity, not its magnitude, and products made from different materials can be compared.

Moraga et al. (2019) found that no circular economy metrics considered the function of a product. Reuse and recycling rates are mostly used to measure circularity without the context of whether the materials are being used efficiently or not. Function, as featured in PwRD, is comparable to the functional unit of a LCA indicator, but it is the cumulative performance of the product over its lifespan. Products with a greater function have a higher PwRD value (expressed in years) and represent a more effective use of resources. The inclusion of demand in the PwRD metric means the societal contribution of a product (through its function) is described without any specific units. Comparisons between different types of products are now valid.

To maintain the synchronous material flows of a circular economy, the number of products required to meet demand must not consume more materials than those allocated for this purpose (Figure 1d). Resource use is considered sustainable if PwRD exceeds the lifespan of the product(s) it represents. The PwRD metric calculates the suitability of products in a circular economy, in which it is assumed materials will be completely recovered and recycled after use. While we make the transition to a circular economy, it can be helpful to compliment PwRD with metrics or other assessments that consider design for reuse, remanufacturing and recycling (Boyer et al., 2021; Linder et al., 2020; Niero and Kalbar, 2019).

2. Material and methods

2.1 General aspects of Performance-weighted abiotic Resource Depletion

Performance-weighted abiotic Resource Depletion differs from established absolute sustainability assessments because it derives a carrying capacity from the availability of resources. A circular economy should prioritise the use of materials already in circulation, but it is accepted that mining operations will continue, which could be considered as consistent with a 'just-transition' towards a sustainable society (as summarised in United Nations, 2017). Mineral reserves have been estimated by the United States Geological Survey (2021), consisting of known inventories of minerals that are economically extractable. Mineral reserves are used for PwRD in preference to total resources (therefore excluding non-economic deposits) so not to suggest the sustainability of products can be improved by further exploration of finite minerals (instead of using recycled materials for instance).

The allocation of mineral reserves is performed according to the demand for the function that is provided by the product (Eq. 1). If global demand is being considered, a share of mineral reserves (M) must be allocated based on the relative need for resources in different sectors. The current market share of a resource can be used for this purpose. Alternatively, the economic value of different sectors can be used, but this disadvantages resource-intensive sectors that represent a small proportion of the economy's value (such as energy production). If demand is being assessed on a regional scale, the allocation of reserves is also scaled proportionally to the population (P) of that region relative to the global population (Eq. 1). Alternative allocation methodologies to differentiate between regions can be used if desired (Hjalsted et al., 2021). The local mineral reserves are not used to calculate regionalised PwRD values so to promote equitable use of commodities.

$$M_{allocated}\,(kg) = M_{total}\,(kg) \cdot Market\ share\ (\%) \cdot \frac{P_{region}}{P_{global}} \qquad \text{(Eq. 1)}$$

The function of a product must be quantifiable and derived from its intended purpose. The two key aspects of a product's function are efficiency and lifespan. A more efficient product will provide a greater output (e.g. food with a higher nutritional content) or complete more tasks within a set time period (e.g. medical scans by a MRI scanner). Function is also proportional to lifespan. If a product maintains the same efficiency for twice its regular lifespan, the function variable in PwRD doubles. Finally, the function and demand variables must match in scope.

2.2 Data and calculations for neodymium in wind turbines case study

The Supplementary Material tabulates the data needed for all the calculations contained in this manuscript. Supplementary Material Data S1-S8 is also provided as an editable spreadsheet containing all relevant calculations. In summary, there were 130 million metric tonnes of rare earth oxide reserves in 2016 (United States Geological Survey, 2021). The proportion of neodymium oxide in rare earth oxide reserves was previously reported as 15.6% by mass (Zhou et al., 2017). This equates to 17 million tonnes of neodymium. The allocation of neodymium to the USA (per capita at 4.3% of global population, see United Nations, 2019) is 750,000 tonnes. Because 13% of annual neodymium use (by mass) is for energy production (Ciacci et al., 2019), the final Nd allocation for energy production in the USA is 98,000 tonnes. Alternatively, the economic allocation of mineral reserves to the power sector (1.46% in 2016) could be used (United Nations ,2018), and the allocation becomes 11,000 tonnes of Nd. The analysis of Fishman and Graedel (2019) provides the quantities of neodymium used to produce wind turbines, i.e. 175.5 kg per MW.

The function of a wind turbine is to generate electricity and so the total energy produced over the lifespan of the wind turbine is required. Equation 2 is the relationship between wind turbine power capacity (C), lifespan (L), and the energy produced (that being the function of a wind turbine). Load rate (also called load factor) is dependent on wind speed. According to the Office of Energy Efficiency and Renewable Energy (2021), the average load rate of USA offshore wind energy was 45.2% in 2016. A medium wind location produces a load rate of 40.9%, and a high wind location 50.1% (Garrett and Rønde, 2015). In the conversion factor, a year is assumed to consist of 365.25 days to compensate for leap years.

$$\text{Function (TWh)} = \text{C (MW)} \cdot \text{L (years)} \cdot \text{Load rate (\%)} \cdot \frac{24\ \text{(hr/day)} \cdot 365.25\ \text{(days/year)}}{1{,}000{,}000\ \text{(MW/TW)}} \qquad \text{(Eq. 2)}$$

USA demand for electricity, including projections to 2050, was also calculated from the data made available by the Office of Energy Efficiency and Renewable Energy (2021). Information on the wind energy capacity and electricity generation for other countries was obtained from BP's Statistical Review of World Energy (BP, 2021). Global energy demand was sourced from the US Energy Information Administration (2020).

3. Results and discussion

3.1 Performance-weighted abiotic Resource Depletion of neodymium in a wind turbine

A wind turbine consists of a foundation and tower, mostly concrete and steel respectively, while the nacelle and rotor blades are produced from a combination of steel, fibre glass and polymers (Schreiber et al., 2019). These materials are generally thought of as abundant and of low concern with respect to resource depletion. Housed in the nacelle is the drive train. To improve reliability, direct-drive wind turbines have been designed that do not have a gear box (Moghadam and Nejad, 2020). The generator in a direct-drive wind turbine requires either ferrite magnets or NdFeB permanent magnets containing rare earth elements (Frankl et al., 2020). Permanent magnets are considered as more reliable, which is an important consideration when the turbine is installed in an offshore location (Pavel et al., 2017).

The rapid expansion of wind power (BP, 2021) is anticipated to create problems for the supply of neodymium, dysprosium, and praseodymium (Li et al., 2020; Pathak et al., 2015). Neodymium (Nd) has received particular attention as the most significant rare earth element by mass in NdFeB permanent magnets (Du and Graedel, 2011; Ciacci et al., 2019). Fishman and Graedel (2019) calculated that over 15 thousand tonnes of Nd will be required to achieve the USA's offshore wind energy expansion strategy to 2050. To understand if the quantity of Nd required to produce wind turbines is justified by the benefit obtained (i.e., electrical energy), Performance-weighted abiotic Resource Depletion (PwRD) can be calculated at the level of an individual wind turbine or a wind farm (Figure 1d). To apply the PwRD metric to other elements found in the permeant magnets of wind turbines, see Supplementary Material Data S9.

Initially considering a single 3.3 MW capacity offshore turbine, operational in the USA in 2016, the expected output (function) depends on the load rate and years in service (Eq. 2). The load rate describes the relationship between the capacity of the wind turbine and the electrical energy obtained. Load rates of a 3.3 MW wind turbine have been provided by Garrett and Rønde (2015) in medium (8 m/s) and high (9.25 m/s) wind scenarios, equal to 40.9% and 50.1% respectively. The average load rate of wind turbines in the USA lies between the medium and high wind scenarios at 45.2% (Office of Energy Efficiency and Renewable Energy, 2021), which would result in 0.26 TWh of electricity over a 20 year lifespan (Figure 2a, example 1). At high wind speeds, 0.29 TWh of electricity is generated over 20 years (Figure 2a, example 2). Function is further improved by design for an extended lifespan (Figure 2a, example 3). The FeNdB magnets typically contain 175.5 kg of Nd per MW (Fishman and Graedel, 2019), but this is projected to decrease with technological advances to 124 kg Nd per MW (Figure 2b).

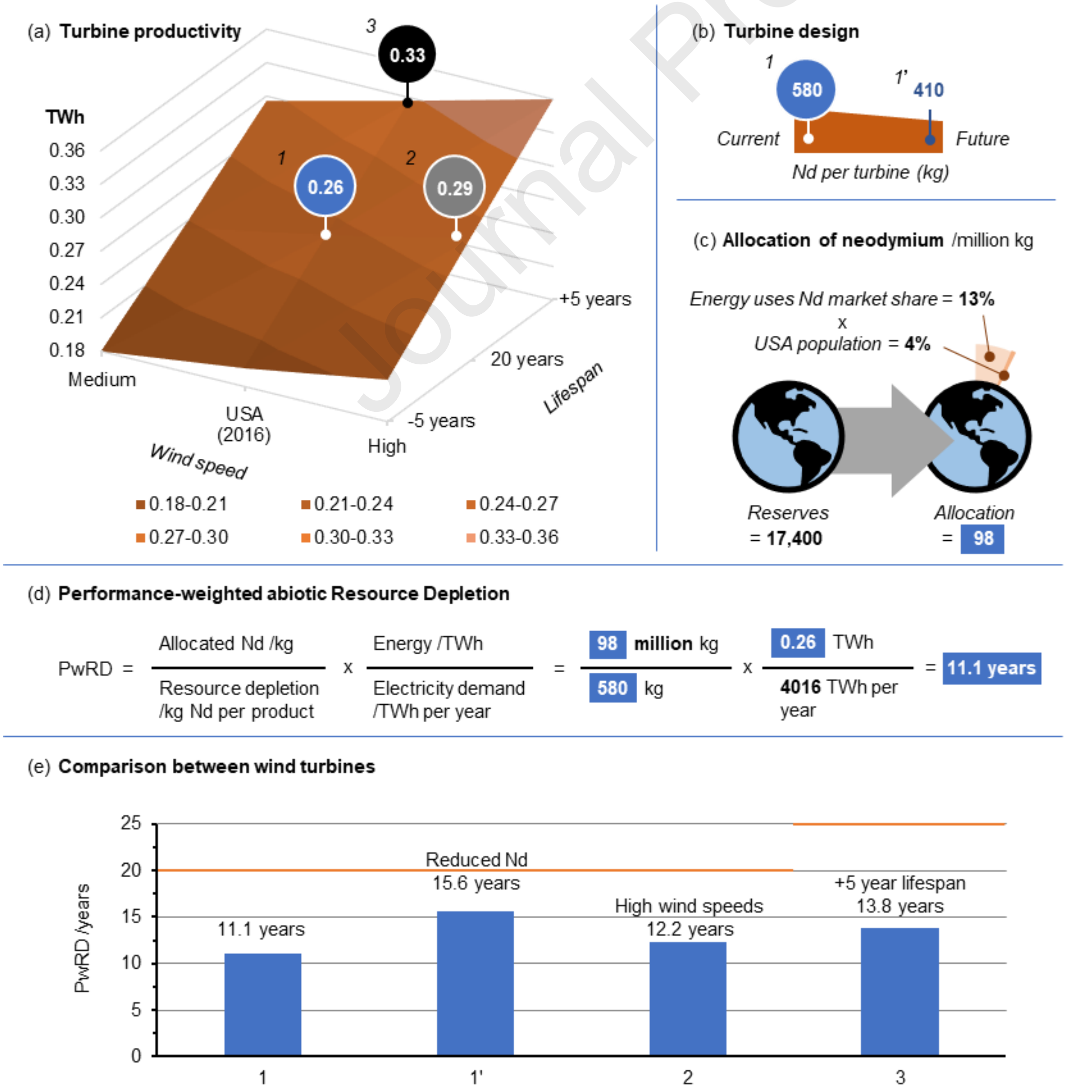


Figure 2. The calculation of PwRD for neodymium (Nd) in wind turbines. (a) Function depending on wind speed and turbine lifespan with three examples. (b) Quantity of Nd per wind turbine. (c) Assignment of Nd reserves to the USA energy sector via Eq. 1. (d) PwRD calculation illustrated for example 1 using USA electricity demand. (e) A comparison between PwRD values (blue bars) and wind turbine lifespan (orange lines).

The allocation of neodymium resources must match the scope of the demand variable, which in this instance is electricity generation in the USA. Electricity demand was 4016 TWh in 2016 according to the US Office of Energy Efficiency and Renewable Energy (2021). Previously, Algunaibet et al. (2019) investigated the environmental sustainability of the USA energy sector and used an economic allocation of Planetary Boundaries (SoSOS) for the purpose of an absolute sustainability analysis as in Figure 1a. This approach is typical of the state-of-the-art (Ryberg et al., 2020). The gross value added (GVA) of the energy sector in the USA was 1.5% of the total economy in 2016. This allocation methodology attributes a much smaller share of Nd reserves to energy generation than many other sectors that do not necessarily need it, for instance real estate at 12.7% and financial services at 7.7% of national GVA (United Nations, 2018). For this reason, an economic allocation has been avoided. Instead, the market share of neodymium for energy production applications (13% according to Ciacci et al., 2019) was used to derive an allocation from the total mineral reserves. This provides a better reflection of where resources are needed, allocating 98 million kg of Nd from 2016 reserves to the production of electricity in the USA (Figure 2c).

The PwRD of neodymium in the first wind turbine example (load rate based on USA average wind speed, 2016, with a 20 year lifespan) is 11.1 years (Figure 2d), or just 1.2 years with the alternative GVA allocation (see Supplementary Material Table S1 entry 1). The choice of allocation method typically creates the greatest discrepancy in absolute sustainability assessments (Hjalsted et al., 2021). The market share allocation is more intuitive for the assessment of resource use, but as with an economic allocation, it can vary year on year, especially for emerging technologies or those approaching redundancy. A clearly defined year on which the assessment is based is essential. For products in use for multiple years, the allocation of reserves is taken from when the product is manufactured.

Figure 2e shows that by locating the wind turbine to benefit from higher wind speeds (PwRD = 12.2 years) or by increasing the wind turbine lifespan by 5 years (PwRD = 13.8 years), the PwRD value increases. However, a realistic reduction to the amount of Nd needed has a greater benefit (PwRD = 15.6 years, example 1’, Figure 2e). Nevertheless, every example in Figure 2 has a PwRD value less than the lifespan of the wind turbine. This indicates the function of the product is insufficient to justify the time the resources are embedded in the product.

If no more than 320 kg Nd was required for a 3.3 MW wind turbine installed in 2016, operating for 20 years under average USA wind speeds, then parity could be reached between PwRD and the actual product lifespan (Supplementary Material Table S1 entry 7). This would be an indication that resources are being used efficiently enough to sustain a circular economy, but would require a significant reduction in Nd use from present levels. Alternatively, 45% recycled Nd content could be used, assuming the total Nd content in the wind turbine is the same as Figure 2, example 1. This represents a significant disparity with the low recycling rates of rare earth elements (Jowitt et al., 2018) which must be improved (Schulze and Buchert, 2016). The limited availability of recycled Nd means improvements to the other variables of the PwRD metric must be considered.

Demand is emphasised in the PwRD metric as a crucial consideration for the sustainability of products. There are optimistic projections of future energy demand and its associated greenhouse gas emissions (Brugger et al., 2021; Barrett et al., 2022), but electricity demand specifically is projected to increase (IEA, 2021). Therefore, the generation of electricity (e.g., by wind turbines) must become more efficient with regards to resource use, not just with respect to emissions, in order to become sustainable.

Extending a product’s lifespan without other measures proportionally increases PwRD (see Figure 2, example 3 compared to example 1). As the rate of electricity generation remains the same, PwRD will still indicate that the wind turbine’s function does not justify the Nd required. The PwRD metric implies product lifespan is irrelevant because in the context of a circular economy it is assumed that the resources will remain in use indefinitely (via recycling when necessary). In reality, permanent magnets are not fully recycled into equal quality materials (Yang et al., 2017). For this reason the ‘Longevity’ metric is a helpful companion to PwRD, as it measures the duration of time materials are used for, accounting for losses from inefficient refurbishment and recycling (Franklin-Johnson et al., 2016). For complex products that are difficult to disassemble and thus recycle, such as wind turbines, extended product lifespan remains a very valuable method to maximise the use of resources, assuming they may not be recovered (Gallagher et al., 2019).

3.2 Multi-product analysis

A Performance-weighted abiotic Resource Depletion (PwRD) calculation can be used to describe a group of products working together to provide a common function, such as a wind farm. To demonstrate, the expansion plans for offshore wind energy in the USA can be analysed (Fishman and Graedel, 2019). It was assumed that the capacity of all the wind turbines is 3.3 MW so that the load rates of the alternative medium and high wind scenarios could be used, and the lifespan is modelled according to a mean average of 20 years with a standard deviation of 5 years. Note that because Nd content is assumed to be linearly correlated with power capacity (Fishman and Graedel, 2019), the size of the wind turbine does not affect its PwRD (subject to changes to the other variables). The assessment of a larger capacity wind turbine is included in Supplementary Material Data S1.

The collective function obtained from a wind farm is derived from each wind turbine's lifespan (Figure 3a). The USA national objective is to install 86 GW capacity of wind turbines by 2050 (Office of Energy Efficiency and Renewable Energy, 2021). It has been estimated that over 15 million kg of Nd will be needed for this purpose (Fishman and Graedel, 2019) (Figure 3b). This includes the expansion of wind farms and the replacement of older wind turbines at end-of-life. No recycling is assumed in the example in Figure 3.

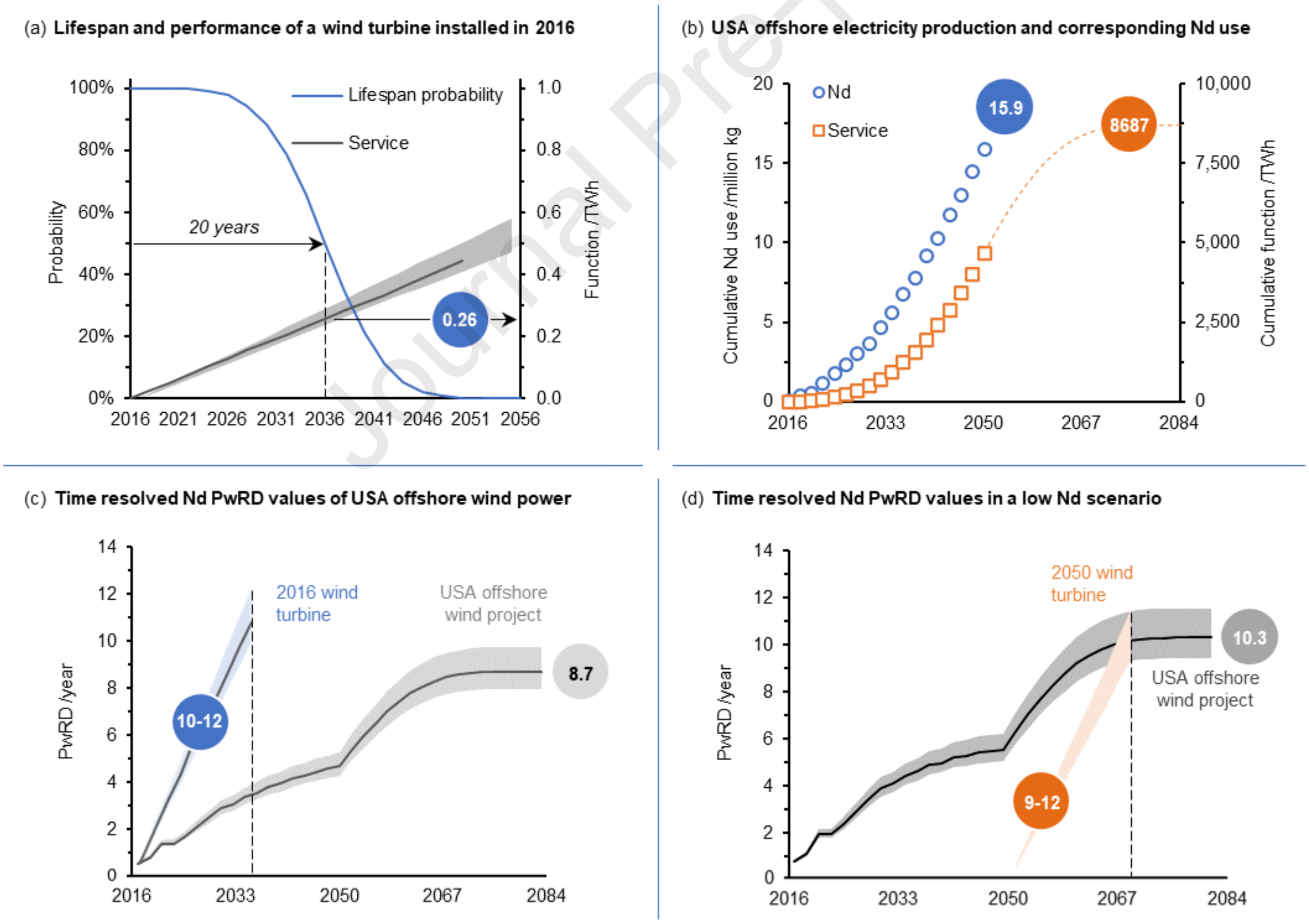


Figure 3. National infrastructure scale PwRD assessment of Nd in wind turbines (USA, 2016-2050). (a) Wind turbine lifespan probability model (blue line) and function (function range between medium and high wind speed shown in grey with USA average represented as a black line) over time (for a single wind turbine installed in 2016). (b) Comparison between cumulative Nd use (circles) and cumulative function (squares) of USA offshore wind energy to 2050. Function projection considers electricity generation from wind turbines installed before 2050 until end-of-life. (c) PwRD value of the USA offshore wind energy project to 2050 and an individual wind turbine built in 2016 (see Supplementary Material Data S3). (d) PwRD value of an alternate low Nd project and an individual wind turbine built in 2050 (see Supplementary Material Data S4). Error range in (c) and (d) is defined between medium and high wind speeds. Capacity expansion and repair of wind turbines both finish in 2050.

When analysing a group of products (described here as a project) with PwRD, the function and resource use increases with time as the products are used and replaced (Figure 3b). The demand category is also time dependant. Meanwhile, the allocated mineral reserves at the start of the project are depleted. In this case study the objective is to evaluate the provision of electricity up to 2050. To be able to conduct this analysis, it was assumed that no further expansion or replacement of wind turbines occurs after 2050. The PwRD of Nd use in USA offshore wind energy was then calculated for each year from 2016 until the value was constant (i.e. when all the wind turbines have been decommissioned). Electricity generation in the relevant year was used as the demand category between 2016 and 2050 inclusive, and then the 2050 value of 5266 TWh/year was applied post-2050, consistent with the aim of the assessment to study USA wind power ambitions to 2050 (Office of Energy Efficiency and Renewable Energy, 2021). A linear reduction in the quantity of Nd needed per MW has been applied between 2020 and 2050 as indicated in Figure 2b (and proposed as a reasonable assumption by Fishman and Graedel, 2019).

Due to the small initial number of wind turbines, mostly newly installed, a low PwRD value is obtained in the early phase of the project (Figure 3c). As function accumulates, the PwRD value increases. Annual fluctuations depend on the rate of wind farm expansion year on year. Once the expansion period is over (2050), the installed wind turbines continue to operate. The continued energy output without further consumption of Nd accelerates the increase in the PwRD value, which reaches a plateau once all the wind turbines installed before the end of 2050 have been decommissioned. The projected PwRD value for the USA offshore wind energy project up to 2050 with respect to Nd is 8.7 years (Figure 3c). The PwRD range (8.0-9.8 years) shown in Figure 3c (and see Supplementary Material Data S3 for full data) includes the bounds set by a medium wind and high wind scenario (Garrett and Rønde, 2015).

The Nd PwRD value attributed to the USA offshore wind energy project is less than for a single wind turbine (as calculated previously, see Figure 2d) because demand for electricity is projected to increase over time to replace energy from fossil fuel combustion. Also, the allocated Nd resources are greatest at the start of the assessment (2016) and depleted as the infrastructure is built and not assumed to be replenished. Finally, the quantity of Nd needed to make each wind turbine is highest in 2016 and so the assessments are not comparable. If a like-for-like comparison is made, a single wind turbine has the same Nd PwRD value as the whole project. Figure 3d shows the PwRD of Nd for a 3.3 MW wind turbine made in 2050 with a 20 year lifespan (also see Supplementary Material Data S4). The range is between 9.4 years at medium wind and 11.6 years at high wind (see Supplementary Material Table S1 entries 12 and 13). The equivalent project-level assessment was performed with a constant Nd per MW and the same PwRD value range as the single wind turbine is reached by the 2080s (Figure 3d). When function is derived from the load rates obtained from average USA wind speeds (Office of Energy Efficiency and Renewable Energy, 2021), the precise PwRD value of the low-Nd content wind turbine project is 10.3 years. If the Nd content of wind turbines is not reduced from present levels, the PwRD value at the project level is 6.9 years, down from the single wind turbine assessment in Figure 2d because of increased demand for electricity in 2050 (Supplementary Material Data S5).

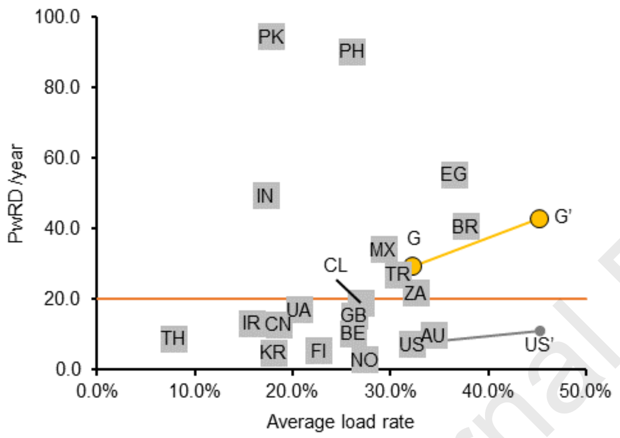
In an alternative scenario, each wind turbine installed to replace a decommissioned product was assumed to require no neodymium from virgin resources (see Supplemental Material Figure S2, and Supplementary Material Data S6). This could be achieved if the wind turbines are remanufactured, retaining and reusing the NdFeB magnets. Otherwise, the variables are the same as the case study in Figure 3c, and the expansion of the project (i.e., increasing the number of wind turbines) still requires Nd resources. The project PwRD value is increased from 8.7 years to 11.3 years, a significant increase but still below the target value of 20 years based on the anticipated product lifespan. Recycled Nd has its greatest impact on the PwRD value of the USA offshore wind project when expansion slows and the replacement of the existing wind turbines becomes the major source of demand for neodymium rather than expanding the project with more wind turbines.

After determining the quantity of Nd required to expand US offshore wind energy, Fishman and Graedel (2019) evaluated the implications of building this new infrastructure on neodymium flows. Performance-weighted abiotic Resource Depletion (PwRD) is a logical extension of this earlier work. By evaluating the performance of products within the conceptual framework of a circular economy, resource depletion can be justified, or conversely, rational product efficiency targets can be set.

3.3 Regional variation of electricity demand and wind turbine sustainability

The Performance-weighted abiotic Resource Depletion (PwRD) values describing the neodymium used to make wind turbines can also be calculated for different regions or on a global scale. The PwRD of Nd in a wind turbine located in USA but assessed on a global scale (with respect to demand and resource allocation) is almost four times greater than those for the USA (43-54 years, otherwise the same as Figure 2 examples 1-3, see Supplementary Material Table S1 entries 14-16). This is due to the 4% of the global population resident in the USA being responsible for 17% of global electricity demand. Additional data for 20 countries confirms Nd PwRD values for wind turbines are highly dependent on demand, which varies by region more so than load rates (Figure 4 and Supplementary Material Data S7). The Philippines and Pakistan have high PwRD values for Nd in wind turbines, both >90 years. This is primarily due to the low electricity use of these countries (per capita, see Figure 4b). The average load rate is a poor indicator of PwRD (Figure 4a) given that demand varies by a much greater magnitude. Note that the load rates were derived from data in BP's Statistical Review of World Energy (BP, 2021), which for the USA is lower than the value from national data sources (Office of Energy Efficiency and Renewable Energy, 2021). Both results are marked on Figure 4.

(a) **Variance of PwRD according to load rate in different countries**



(b) **Variance of PwRD according to demand in different countries**

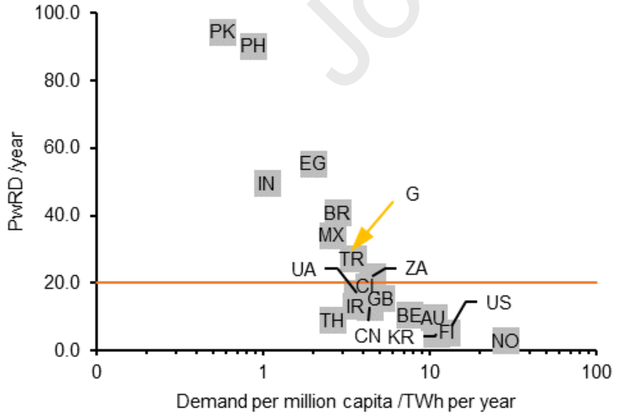


Figure 4. Regional comparison of PwRD values of wind turbines with respect to Nd. Countries are labelled with their two-letter abbreviation. (a) As a function of load rate. Global value (G, gold data point) is based a wind turbine installed in USA but worldwide electricity demand. Data for USA and the global example also shown for higher load rate (US' and G'). (b) As a function of demand per capita. Global value (G) is obscured and so it is indicated by the tip of the gold arrow.

Demand for the function of products acts as a weighting factor in the PwRD metric by which to judge the regionalised sustainability of resource use. Global resources have been assigned on an 'equal per capita' basis because a larger population warrants a greater share of neodymium for electricity generation, and so it is demand per capita specifically that differentiates the PwRD values between different regions. The findings in Figure 4 suggest the imbalance of energy use between countries must be addressed with the goal of an overall global reduction. For this to be achieved equitably, we must consider the cultural, geographic and economic differences between countries. The former is highly aspirational (Grasso, 2012), with a per capita allocation for safe operating spaces generally preferred (O'Neill et al., 2018); the latter can be explored with existing methods (Hjalsted et al., 2021). An economic weighting to the allocation of neodymium reserves based on Gross Domestic Product (GDP) is provided in Supplementary Material Data S8. The methodology is based on an 'ability to pay' concept used previously to determine the SoSOS in absolute sustainability assessments as in Figure 1a (Hjalsted et al., 2021). Countries with a GDP per capita significantly below the global average are allocated a higher quantity of Nd reserves than they would according only to population. For all other countries the allocation is reduced proportionally with increasing GDP per capita. This allocation method has a drastic effect on PwRD values. In the case of Pakistan, PwRD of Nd in a wind turbine increases from 95 years to 171 years. The corresponding USA wind turbine has a reduced Nd PwRD of 0.3 years (Supplementary Material Data S8). It is recommended when the purpose of the study is to improve product design, the standard format of the PwRD metric is used (Figure 2d). However, modified assessments can be helpful to evaluate the socioeconomic factors regarding the sustainability of resource use.

Consumer motivations (Guo et al., 2018; Azarova et al., 2020), energy efficient technologies and products (An et al., 2020; Lange et al., 2020), and government policy (Qarnain et al., 2021) all have a role in controlling demand for electricity and facilitating sustainable energy generation. However, USA electricity demand in 2050 would have to be about two-thirds of 2016 demand for a wind turbine utilising 410 kg Nd to be sustainable (see Supplementary Material Table S1 entry 20), a large swing from the anticipated increase in demand for electricity of over 30%. Therefore, is it more realistic that reductions to Nd use and the recycling of FeNdB magnets could provide the necessary improvements. It is important when considering low Nd technologies for wind turbines that alternative materials are assessed too. The PwRD of other resources used to produce wind turbines can be calculated in Supplementary Material Data S9. Note that precise market share data is sometimes unavailable, which is a barrier to the implementation of PwRD assessments. Nevertheless, there is preliminary evidence to suggest the depletion of other rare earth elements and cobalt to make wind turbines is concerning. In this regard, it is important to note that any improvements to product efficiency, or a reduction in demand, increases the PwRD of all the materials in a product proportionally. To enable a circular economy, it is of great benefit to increase the function of products regardless of their purpose or what they are made from.

Conclusion

Our present-day economic system relies on waste and compensating for waste with more resource use to maximise capital accumulation. A circular economy eliminates unnecessary waste, and therefore careful resource management is required to generate value. Performance-weighted abiotic Resource Depletion (PwRD) establishes a relationship between resource use and the performance of products to derive a measurement of sustainability in a circular economy. The normalisation of these variables with the allocated mineral reserves and demand for the function provided by the product eliminates functional units and mineral-specific quantities. This permits a direct comparison between products made for different applications containing different materials. The decoupling of resource use from economic growth, essential for a circular economy, is conceptualised in the PwRD metric by allocating reserves to different purposes based on need, not profit. The consideration of a product's function emphasises the role of product design to improve performance and durability, which is generally lacking from other contemporary circular economy metrics.

The PwRD value of neodymium in a USA wind turbine is typically 11-16 years. For neodymium reserves to be used efficiently enough to sustain a circular economy, wind turbines must have a PwRD of 20 years or more and designed so that resources are recoverable at end-of-life. The following actions are pertinent for the aim of increasing PwRD values: accelerating the development of low or rare earth-free magnets (Cui et al., 2018), prioritising design for recycling provided that efficient recycling technologies can be commercialised (Jensen et al., 2020; Omodara et al., 2019; Velenturf, 2021), or otherwise, substantially increase the lifespan of turbines. From a policy perspective, demand for the function of products can also be evaluated with PwRD, and national targets for sustainable consumption can be derived from the resource depletion incurred to deliver different technologies. The impact of decision making, such as the repowering of wind farms (the early decommissioning of wind turbines in favour of newer models) can also be measured and resource use optimised.

The limitations of the PwRD metric are generally the same as similar tools. There is no consensus on allocation methods (e.g., of resource reserves) in absolute sustainability assessments. Mineral reserves have been chosen as the basis of normalising resource use in this work, which is debatable given the discovery and extraction of resources continues. Other significant sources of uncertainty are the true lifespan of products (which is highly dependent on user behaviour, or in the case of infrastructure projects, decision makers), and changes to demand (both annually and regionally). Despite the aforementioned constraints, PwRD offers a resource-use perspective on circularity that is missing from recycling-based metrics, and quantifies the actions needed to design and use products sustainably.

Author contributions

J.S.: Conceptualization, Data curation; Formal analysis; Investigation; Methodology; Supervision; Validation; Visualization; Writing - original draft; Writing - review & editing. G.T.G.: Data curation; Formal analysis; Investigation. A.P.M.V.: Formal analysis; Investigation; Validation; Writing - original draft; Writing - review & editing.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: