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Resourcing the fairytale country with wind power: a dynamic material flow analysis

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ABSTRACT

Wind energy is key to addressing the global climate challenge, but its development is subject to potential constraints of finite primary materials. Prior studies on material demand forecasting of wind power development are often limited to a few materials and with low technological resolution, thus hindering a comprehensive understanding of the impact of micro-engineering parameters on the
resource implications of wind energy. In this study, we developed a component-by-component and stock-driven prospective material flow analysis model, and used bottom-up data on engineering parameters and wind power capacities to characterize the materials demand and secondary supply potentials of wind energy development in Denmark, a pioneering and leading country in wind power. We also explicitly addressed the uncertainties in the prospective modeling by the means of statistical estimation and sensitivity analysis methods. Our results reveal increasing challenges of materials provision and end-of-life (EoL) management in Denmark’s ambitious transition towards 100% renewable energy in the next decades. Harnessing potential secondary resource supply from EoL and extending lifetime could curtail the primary material demand, but they could not fully alleviate the material supply risk. Such a model framework that considers bottom-up engineering parameters with increased precision could be applied to other emerging technologies and help reveal synergies and trade-offs of relevant resource, energy, and climate strategies in the future renewable energy and climate transition.

**GRAPHICAL ABSTRACT**
1. INTRODUCTION

Wind energy technologies are often regarded as an important enabler in many low-carbon scenarios, such as the International Energy Agency (IEA)’s Sustainable Development scenario\(^1\) and the global emission mitigation pathways in the Intergovernmental Panel on Climate Change (IPCC)’s 1.5°C special report\(^2\). However, transitioning towards a low-carbon society, where large amounts of renewable energy infrastructure are urgently needed, requires vast amounts of metals and minerals\(^3\).

Such resource implications\(^4-7\) of energy transition and consequent supply security\(^8-11\) and embodied environmental impacts\(^12,13\) have gained increasing attention in recent years.

For example, Denmark, a pioneer in developing commercial wind power since the 1970s’ oil crisis, has built up an energy system of which already about 48% of electricity is from wind in 2017\(^14,15\). The intermittent yet abundant wind energy in Denmark will continue to play a major role for achieving the Danish government’s ambition to have a ‘100% renewable’ energy system by 2050\(^16,17\). Understanding potential resource supply bottlenecks, reliance on foreign mineral resources, and secondary materials provision is therefore an important and timely topic for both the Danish wind energy sector and Denmark’s energy and climate policy.

Construction and maintenance of wind power systems needs large quantities of raw materials mainly due to large-scale deployment of wind turbines and infrastructure on land or at sea\(^18\). In particular, two rare earth elements (neodymium and dysprosium) mainly used in permanent magnets have raised special concerns in the wind energy sector\(^10,19,20\) due to over-concentration of rare earth’s supply in China\(^21\), sustainability of upstream mining and production processes\(^22\), and complexity of wind
turbines’ supply chain. Moreover, the wind energy sector also faces increasing challenges in both meeting future demands for several base metals (e.g., copper used in transmission) and managing mounting end-of-life (EoL) materials (e.g., glass fiber in blades) arising from decommissioned wind turbines.

A variety of methods have been used to translate wind energy scenarios into material demand. If the annual newly installed capacity of wind turbines is given, its associated material demand is often directly determined by material intensity per capacity unit. If annual installed capacity is not given, its associated material demand can be derived from a Life Cycle Assessment (LCA) based input-output method, an economic model, or a dynamic material flow analysis (MFA) model. The dynamic MFA model has been increasingly used to explore material requirements of wind energy provisioning on a global scale, a country scale (e.g., the US, France, and Germany), or a country scale with a regional resolution. The principle of mass balance constitutes the foundation of any MFA, so that the annual newly installed capacity (‘inflow’) and annual decommissioned capacity (‘outflow’) of wind turbines are driven by their lifetime and the expansion and replacement of the installed wind power capacity (‘stock’), which has also been widely used in other anthropogenic stock studies.

However, the current practice of modeling raw material requirement or secondary material availability in different wind energy technologies generally overlooks the hierarchical, layered characteristics of wind power systems. This is important because materials embedded in a technology system are usually distributed in its subsystem or subcomponents with varying compositions and recycling potentials. In the case of wind power systems, materials employed in a wind turbine are distributed in its...
subcomponents such as rotor, tower, and nacelle, and their mass is largely determined by turbine size (e.g., rotor diameter or hub height) and capacity\textsuperscript{13,40}. These constraining factors and their leverages on the sustainability and resilience of the wind energy provisioning should be fully examined. Such information would enable wind turbine manufacturers, material suppliers, recyclers, end users, and policy makers to plan their material-related policies with a comprehensive understanding on a range of important aspects related to wind energy provisioning, such as secondary material supply, technological development, and material efficiency.

Here, we developed a component-by-component and stock-driven prospective MFA model to characterize material requirements and secondary material potentials of different Danish wind energy development scenarios. Based on two datasets that cover a range of micro-engineering parameters (e.g., capacity, rotor diameter, hub height, rotor weight, nacelle weight, and tower weight) of wind turbines installed in Denmark and worldwide, we established empirical regressions among these parameters in order to address the size scaling effects of wind turbines. We considered important drivers such as growing average capacity, material efficiency improvements, changing market share, and lifetime extension, and aimed to address the following specific questions:

1. How much materials would be needed for Denmark’s wind energy systems in its different ‘100% renewable’ transition pathways?

2. What are the potentials of secondary materials supply from future Danish wind energy systems?

3. How would the above-mentioned key drivers affect material requirements and secondary material supply?
2. MATERIALS AND METHODS

2.1. System definition and modeling framework

The system definition and modeling framework for translating energy scenarios into material requirements of Denmark’s wind energy system are delineated in Figure 1. The subsystems considered cover wind turbines, foundations, transformer stations, and internal cables (connecting individual wind turbines to the transformer station). Onshore and offshore wind turbines are differentiated. Six bulk materials (steel, cast iron, nonferrous metals, polymer materials, fiberglass, and concrete) and two critical materials (neodymium and dysprosium) which represent the majority of materials used in different components are included in our model.

We employed a stock-driven prospective MFA approach\textsuperscript{41,42} to simulating future flows (i.e., new installation and decommission) of onshore and offshore wind power capacities from 2018 to 2050. For bulk materials, we developed a component-level modeling approach to converting wind power capacities into material requirements, taking into account relationships among the engineering parameters of wind turbines. For critical materials, we took into account the impacts of adopting wind turbine technologies that use a permanent magnet generator, as well as the improvement of its material intensity, on material demand and availability of secondary materials.
2.2. Energy scenarios and stock-driven modeling

The Danish government has the ambition to achieve a ‘100% renewable’ energy system by 2050\textsuperscript{16}. The Danish Energy Agency (DEA) has accordingly developed four fossil fuel free scenarios, plus a reference fossil fuel scenario where all policy targets are disregarded\textsuperscript{16}. In parallel, the Danish Society of Engineers (IDA) developed a ‘Smart Energy System’ strategy for the same ‘100% renewable’ target,
taking into account the cross-sectoral interaction of electricity, heat, gas and transport sectors. These five ‘100% renewable’ scenarios all imply a high reliance on wind energy or bioenergy.

We extracted future in-use capacities of onshore and offshore wind power systems from the energy scenarios developed by the DEA and the IDA. Figure 2b demonstrates the smooth transitions of the future Danish wind energy systems under six different scenarios. These energy scenarios are mainly characterized by Denmark’s limited biomass resource and abundant but intermittent wind power generation.

The DEA has outlined four potential fossil fuel free scenarios (i.e., Biomass, Biomass+, Wind, and Hydrogen) for Denmark’s ‘100% renewable’ ambition. Plus, a Fossil scenario has been developed in parallel, neglecting all national targets and therefore continuing the consumption of fossil fuels. The four fossil fuel free scenarios are constructed from a biomass perspective, and assume that a certain portion of onshore capacities will be replaced by offshore capacities, as summarized below.

- The Biomass scenario assumes a moderate electrification but an increased reliance on imported bioenergy.
- The Biomass+ scenario assumes a higher reliance on imported bioenergy compared to the Biomass scenario.
- The Wind scenario assumes a massive electrification in the transportation sector and the heating sectors, thereby expecting a constant increase in wind power capacities and a limited biomass demand.
The **Hydrogen** scenario assumes that Denmark will heavily rely on hydrogen technologies to convert wind energy into hydrogen that is further used for hydrogenation of carbon sources.

The IDA developed an alternative scenario (hereafter named as the **IDA** scenario) which is between the **Wind** scenario and the **Hydrogen** scenario\(^7\). The **IDA** scenario assumes that more efficient electrolysis technologies will be adopted and thus less wind power will be needed compared to the **Hydrogen** scenario. While the onshore capacities in the five DEA scenarios will decrease to 3.5 GW, the **IDA** scenario assumes that the onshore capacities will expand to 5 GW by 2050. The rationale for this assumption is buying up buildings to create more space for onshore wind turbines is socio-economically more attractive than building offshore wind power capacities.

**Figure 2.** In-use capacities of Danish wind power systems (onshore and offshore) a) from 1977 to 2017 and b) from 2018 to 2050 in the **Hydrogen**, **IDA**, **Wind**, **Fossil**, **Biomass**, and **Biomass+** scenarios.
Note: for onshore capacity scenarios, the lines of the Wind, Biomass, Biomass+, Hydrogen, and IDA scenarios are overlaid by the line of Fossil scenario, because they use the same target value.

A stock-driven model was used to determine the annual new and decommissioned capacities of wind turbines, based on a stock-flow modeling framework\textsuperscript{41-43} and assumed lifetime. Mathematically, the relationship between the new and decommissioned capacities can be expressed as a convolution, respecting the mass-balance principle. Therefore, the new and decommissioned capacities are driven by the assumed development of in-use capacities and lifetime, according to the equations below.

\begin{align*}
\text{Inflow}_t &= \text{Stock}_t - \text{Stock}_{t-1} + \text{Outflow}_t \quad (1) \\
\text{Outflow}_t &= \sum_{t' = t-1}^{t-1} \text{Inflow}_{t'} \times (1 - S_{t-t'}) \quad (2)
\end{align*}

where \(\text{Inflow}_t\) or \(\text{Inflow}_{t'}\) refers to the new capacities at year \(t\) or \(t'\); \(\text{Stock}_t\) or \(\text{Stock}_{t-1}\) refers to the in-use capacities of wind turbines at year \(t\) or \(t-1\); \(\text{Outflow}_t\) refers to the decommissioned capacities at year \(t\); and \(S_{t-t'}\) refers to the probability that the previously installed capacities reach their end-of-life after \(t-t'\) years.

A Weibull distribution was used to determine the lifetime distribution of wind turbines and the corresponding survival function (see Figure S1 and Table S1 in the Supporting Information). The average lifetime of wind turbines in the Danish energy system is 17.8 years, which is slightly lower than assumptions used in prior studies\textsuperscript{6,35}, due mainly to the fact that as a pioneering country in wind energy development, certain amounts of wind turbines installed in Denmark are pilot projects with a shorter lifetime.
2.3. Empirical regressions of engineering parameters

The current trend shows that the size of wind turbines is continuously scaling up\textsuperscript{44}, which has considerable impacts on the mass of wind turbines. The technological trend of turbine size was taken from the prediction made by the DEA\textsuperscript{45}. The average capacity of onshore wind turbines will increase to 4 MW by 2030 and 5 MW by 2050; meanwhile, the average capacity of offshore wind turbines will increase to 12 MW by 2030 and 15 MW by 2050. We used two large sample datasets to derive empirical relationships among engineering parameters of wind turbines, as detailed below.

1. Size determination based on the Danish Master Data Register of Wind Turbines\textsuperscript{46}: we determined the empirical relationships between the capacity (C) and the hub height (H), and the capacity (C) and the rotor diameter (D);

2. Mass determination based on The Wind Power database\textsuperscript{47}: we determined the empirical relationships between the rotor diameter (D) and the rotor weight, the rotor diameter (D) and the nacelle weight, and the square of rotor diameter (D\textsuperscript{2}) multiplied by hub height (H) and the tower weight.

Figure 3 demonstrates the size scaling effects on wind turbine’s mass. For example, a scaling factor (the exponent of a power function) smaller than 1 is observed in the empirical regressions between capacity and rotor diameter for both onshore wind turbines and offshore wind turbines. This means a 1% increase in average capacity will result in a 0.49% increase in onshore wind turbines’ rotor diameter and a 0.59% increase in offshore wind turbines’ rotor diameter, respectively. Similar size scaling effects can be observed in the empirical regressions between capacity and hub height, but its
scaling factor for onshore wind turbines (0.39) is larger than offshore wind turbines (0.34). However, a scaling factor larger than 2 is observed in the empirical regression between rotor diameter and rotor weight, as well as the empirical regression between rotor meter and nacelle weight. This means, for example, a 1% increase in rotor diameter will result in a 2.01% increase in rotor weight for onshore wind turbines and a 2.14% increase in rotor weight for offshore wind turbines. The scaling factor of the empirical regression regarding tower weight is less than 1. In general, the empirical regression equations in our study are in good agreement with a prior study\textsuperscript{40} which is based on 12 wind turbines.
Figure 3. Empirical regressions among engineering parameters of wind turbines, a) between capacity and rotor diameter; b) between capacity and hub height; c) between rotor diameter and rotor weight; d) between rotor diameter and nacelle weight; and e) between the square of rotor diameter multiplied by hub height and the tower weight. D: rotor diameter; H: hub height. Sample size: Danish Master Data Register of Wind Turbines (n=9450) and The Wind Power (n=1451).
2.4. Material composition specification

Material composition data were extracted from Life Cycle Inventory (LCI) data documented in various Life Cycle Assessment (LCA) studies. Sources of LCI data and bulk material intensities are detailed in Section 4 of the Supporting Information. Materials used in foundation, internal cables, and transformers were computed based on the ratio of their mass to wind turbines’ mass.

For the two critical materials (i.e., neodymium and dysprosium), we took the averages of material intensities used in prior studies (see Table S3 in the Supporting Information) according to the assumptions from a prior study\(^{36}\). In general, the hybrid-drive generators that are mainly adopted in onshore wind system, use about one-third the mass of their direct-drive counterparts that are mainly adopted in offshore wind system\(^{20}\); therefore, we assumed that the intensity of neodymium and dysprosium in onshore wind turbines is one-third the intensity of offshore wind turbines. In addition, we assumed that the neodymium intensity and dysprosium intensity will decrease by 30% up to 2050\(^{36}\).

Due to the availability of national data, the market shares of wind turbines in Denmark based on permanent magnet generators are assumed to be the same as the entire European market (17% of onshore and 6% of offshore), according to the JRC Wind Energy Status Report\(^{48}\).

2.5. Uncertainties and sensitivity analysis

Our model results depend on assumptions on a few key parameters, such as the market share of permanent magnet based generators and the lifetime of wind turbines. Therefore, we assessed the impacts of permanent magnet based generators’ market share (increased to 50%) and lifetime extension (extended to 20 or 25 years) on simulation results. We also examined the impacts of statistical
uncertainties in the empirical regressions and the lifetime distribution on the simulation outputs. Details on statistical uncertainties in engineering parameters of wind turbines are tabulated in Table S1 in the Supporting Information. Based on the variation of the statistical uncertainties, a one-factor-at-a-time sensitivity analysis was conducted to assess the effect of each individual parameter on simulation outputs. In other words, one individual parameter was changed while the other parameters remained the same.

3. RESULTS AND DISCUSSION

3.1. New capacities, decommissioned capacities, and size scaling effects

Figure 4 shows newly installed wind power capacities (for expansion and replacement) and decommissioned capacities from 2018 to 2050 under the six scenarios. Overall, the newly installed capacity under the six scenarios will reach its bottom in approximately 2027 and then start picking up. The newly installed capacity under the Biomass, Biomass+, and Fossil scenarios will remain largely unchanged at 0.61, 0.35, and 0.54 GW in 2050, respectively; while the newly installed capacity under the Wind, Hydrogen, and IDA scenarios will grow to 1.57, 2.04, and 1.74 GW in 2050, respectively. Under the Wind, Hydrogen, and IDA scenarios, the expansion of wind power systems drives the demand for newly installed capacity, while under the Biomass, Biomass+, and Fossil scenarios, the replacement of obsolete wind energy capacities is the main driver. Concurrently, the decommissioned capacity under the Hydrogen, IDA, and Wind scenarios will slightly increase, but it keeps relatively stable under the Fossil, Biomass, and Biomass+ scenarios after approximately 2027.
Figure 4. Newly installed wind power capacity (for expansion and replacement) and decommissioned capacity from 2018 to 2050 in the Hydrogen, IDA, Wind, Fossil, Biomass, and Biomass+ scenarios.

Although the increases in wind turbine capacity will marginally lead to less increases in wind turbine dimensions (i.e., rotor diameter and hub height), this effect is canceled out by the exponential increases in wind turbine mass resulting from the growing dimensions (see Figure 3). The empirical regressions derived from engineering parameters of wind turbines add up to varying size scaling effects. As shown in Figure S2 in the Supporting Information, the size scaling effects of onshore wind turbines will give rise to a small material efficiency improvement, as their average capacity increases from 3.6 MW to 5 MW. During 2018-2050, the mass per MW of onshore wind turbines will slightly decrease from 104.87
t/MW to 102.14 t/MW. On the contrary, the size scaling effects of offshore wind turbines will lead to a modest increase in material intensities. The mass per MW of offshore wind turbines will marginally increase from 149.95 t/MW to 161.64 t/MW during the same period. The ~12 t/MW growth in the mass per MW of offshore wind turbines is mainly attributed to size increases in rotor and nacelle.

The expected effects of upscaling wind turbines indicate that their material requirements will increase if more offshore ones are to be erected, which has been well-considered in the prospective modeling in our study. These effects have been recognized in several LCA studies related to wind energy. Although one of the two datasets in our study is Denmark-specific, the observed size scaling effects could be applied to investigate material uses of wind energy provisioning in other regions or countries, because wind turbines installed in Denmark cover a wide range of models and manufacturers. More importantly, incorporating the micro-engineering parameters in the prospective modeling can help understand the impacts of design or technological progress on the material demand and secondary supply of wind energy provisioning.

3.2. Material requirements and potential secondary materials supply

Figure 5 assembles the results of material requirements (inflows) and potential secondary materials supply (outflows) during 2018-2050 under the six scenarios. Several key observations on the trends of inflows and outflows are detailed as below.

- The inflows of bulk materials (concrete, steel, cast iron, nonferrous metals, polymer materials, and fiberglass) under the Hydrogen, IDA, and Wind scenarios will increase by 413.31%, 211.91%, and 328.83% respectively. Meanwhile, the outflows of bulk materials will increase by
52.90%, 49.86%, and 33.15% respectively. On the contrary, the inflows of bulk materials will increase at a slower rate under the Fossil and Biomass scenarios, or fall slightly under the Biomass+ scenario. Meanwhile, the outflows of bulk materials will decrease by 23.71%, 15.98%, and 37.76% respectively.

- The inflow of neodymium under the Hydrogen, IDA, and Wind scenarios will climb to 14.50 tonne yr\(^{-1}\), 12.36 tonne yr\(^{-1}\), and 11.15 tonne yr\(^{-1}\) respectively. Meanwhile, the outflow of neodymium will swell to 5.64 tonne yr\(^{-1}\), 5.71 tonne yr\(^{-1}\), and 4.98 tonne yr\(^{-1}\) respectively. On the contrary, the inflow of neodymium will decrease at first and increase to 3.78 tonne yr\(^{-1}\) and 4.28 tonne yr\(^{-1}\) under the Fossil and Biomass scenarios respectively, or decrease to 2.46 tonne yr\(^{-1}\) under the Biomass+ scenario; meanwhile, the outflow of neodymium will climb up and stabilize at a certain level under the Fossil (3.07 tonne yr\(^{-1}\)), Biomass (3.34 tonne yr\(^{-1}\)), and Biomass+ (2.60 tonne yr\(^{-1}\)) scenarios.

- A similar trend is observed in the inflow and outflow of dysprosium. The inflow of dysprosium under the Hydrogen, IDA, and Wind scenarios will eventually climb to 1.73 tonne yr\(^{-1}\), 1.48 tonne yr\(^{-1}\), and 1.33 tonne yr\(^{-1}\) respectively. Meanwhile, the outflow of dysprosium will simultaneously grow to 0.67 tonne yr\(^{-1}\), 0.68 tonne yr\(^{-1}\), and 0.59 tonne yr\(^{-1}\) respectively. On the contrary, the inflow of dysprosium will decrease at first and increase to 0.45 tonne yr\(^{-1}\) and 0.51 tonne yr\(^{-1}\) under the Fossil and Biomass scenarios respectively, or decrease to 0.29 tonne yr\(^{-1}\) under the Biomass+ scenario; meanwhile, the outflow of dysprosium will climb up and stabilize at a certain level under the Fossil (0.37 tonne yr\(^{-1}\)), Biomass (0.40 tonne yr\(^{-1}\)), and Biomass+ (0.31 tonne yr\(^{-1}\)) scenarios.
- The aforementioned observations indicate that, in the case of both bulk materials and critical materials, the gap between their inflow and outflow will be enlarged under the Hydrogen, IDA, and Wind scenarios, and it will still be enlarged but to a lesser degree under the Fossil, Biomass, and Biomass+ scenarios.

**Figure 5.** Material requirements (inflows) for newly installed capacity and potential secondary materials supply (outflows) from decommissioned capacity from 2018 to 2050 in the Hydrogen, IDA, Wind, Fossil, Biomass, and Biomass+ scenarios. Note: positive numbers represent inflows and negatives represent outflows. Nd: neodymium. Dy: dysprosium.
Evidently, Denmark’s wind energy sector would be exposed to high supply risk if the country is transitioning towards a wind powered economy in all 100% renewable energy scenarios. To demonstrate the imbalance between material requirements and potential secondary material supply, as well as its dynamics over time, we propose an indicator ‘circularity potential’, which is defined by the ratio of outflow to inflow. This indicator measures not only the material supply risk that the wind energy sector is exposed to, but also to what extent the secondary material supply can potentially mitigate the material supply risk. We could observe that the ‘circularity potential’ of both bulk materials and critical materials in the Fossil, Biomass, and Biomass+ scenarios is consistently higher than that in the Hydrogen, IDA, and Wind scenarios, because in-use capacities in the former scenarios will remain stable or only slightly increase and decommissioned capacities will gradually rise. It can be observed that the ‘circularity potential’ of critical materials (neodymium and dysprosium) under the Hydrogen, IDA, and Wind scenarios will increase from 0.24%, 0.17%, and 0.26%, peak at 45.5%, 54.30%, and 51.31%, and fall to 38.91%, 46.23%, and 44.68%, respectively. On the contrary, the ‘circularity potential’ of critical materials under the Fossil, Biomass, and Biomass+ scenarios will climb from 0.34%, 0.23%, and 0.28% to 81.27%, 77.89%, and 105.55%, respectively. The consistently higher ‘circularity potential’ of critical materials is explained by two factors: mounting secondary supply from decommissioned wind turbines and less material intensities of new turbines (see Table S3 in the Supporting Information). Although Denmark is sending its wastes abroad (e.g., Germany, Turkey, Sweden, Spain, or China), the ‘circularity potential’ can help understand to what extent circular economy strategies reduce raw material requirement in Denmark if the country is to stipulate extended producer responsibility (EPR) policies expanded across national borders. The consistently higher ‘circularity potential’ of critical materials also indicates that the supply risk of wind power provision can be substantially reduced by implementing relevant circular economy strategies.
It should be noted that harnessing secondary materials in decommissioned wind turbines, as identified in the ‘circularity potential’, depends on many other socioeconomic and technological factors as well. For example, a wide range of circular economy measures on fiberglass were identified in a prior study, such as reuse, resize, recycle, recovery, and conversion. However, commercial applications of secondary fiberglass are extremely limited, due to its low-value and complex composition, the lack of material composition documentation, the long transportation distance, as well as the underdevelopment of extended producer responsibility regulations. Another typical example is the currently negligible recycling of neodymium and dysprosium, because their recycling technologies are still in their infancy. Reuse of permanent magnet seems to be a better option, but the size and materials specifications of the permanent magnets available from decommissioned wind turbines might not fit future wind turbine design. Therefore, to deliver reliable secondary material supply, several framework conditions (e.g., regulations, logistics management, recycling infrastructure, appropriate design for reuse, and enough economic incentives) need to be considered and improved, and different EoL options for decommissioned wind turbines should be scrutinized and optimized. Since Denmark is one of the pioneers in developing wind power, the resource implications derived from our results can be transplanted to other countries who have the same ambition to develop large-scale wind power systems.

### 3.3. Impacts of increasing market share and lifetime extension

The market share of wind turbines that use permanent magnet generators would systematically alter the landscape of neodymium demand (inflows) and potential secondary neodymium supply (outflows) (Figure 6a; and results on dysprosium in the Supporting Information). Figure 6a shows that, if the
market share gradually increases to 50% by 2050, annual neodymium inflows will accordingly grow to
114.28 tonnes yr\(^{-1}\) (Hydrogen scenario; 788.14% compared to market share unchanged and the same
comparison hereafter), 93.27 tonnes yr\(^{-1}\) (IDA scenario; 754.61%), 86.36 tonnes yr\(^{-1}\) (Wind scenario;
774.53%), 24.93 tonnes yr\(^{-1}\) (Fossil scenario; 659.52%), 29.09 tonnes yr\(^{-1}\) (Biomass scenario;
679.67%), and 13.92 tonnes yr\(^{-1}\) (Biomass+ scenario; 565.85%), respectively. In particular, the impacts
of increasing market share on neodymium inflows under the Hydrogen, IDA, and Wind scenarios are
augmented by the expanding capacities, with the inflows in offshore wind turbines contributing the
most. Annual neodymium outflows will grow from negligible amounts (less than 1 tonne) to 7.36-
21.41 tonnes under the six scenarios. Under the Hydrogen, IDA, and Wind scenarios, the increasing
market share will consistently reduce the ‘circularity potential’ of neodymium, reaching 18.74%,
21.67%, and 21.20% by 2050, respectively. These results suggest that the penetration of wind
technologies that use a permanent magnet generator will aggravate the supply gaps of neodymium and
dysprosium.

On the contrary, lifetime extension will universally scale down the inflows and outflows of neodymium
(see Figure 6b) across the six scenarios. Results on the other seven materials (i.e., dysprosium,
concrete, steel, cast iron, nonferrous metals, polymer materials, and fiberglass) are documented in the
Supporting Information. If the average lifetime is extended to 20 years, the cumulative neodymium
inflows will decrease to 222 tonnes (Hydrogen scenario; 93.48% compared to lifetime unchanged and
the same comparison hereafter), 217 tonnes (IDA scenario; 93.08%), 187 tonnes (Wind scenario;
92.84%), 97 tonnes (Fossil scenario; 89.68%), 108 tonnes (Biomass scenario; 90.19%), and 79 tonnes
(Biomass+ scenario; 88.32%), respectively; if the average lifetime is extended to 25 years, the
cumulative neodymium demands will further decrease to 195 tonnes (Hydrogen scenario; 82.31%), 188
tonnes (IDA scenario; 81.01%), 162 tonnes (Wind scenario; 80.47%), 77 tonnes (Fossil scenario; 71.42%), 87 tonnes (Biomass scenario; 72.84%), and 60 tonnes (Biomass+ scenario; 67.53%), respectively. However, the cumulative neodymium outflows will scale down simultaneously if the average lifetime is extended, which makes the difference between the cumulative inflows and the cumulative outflows almost unchanged. The results suggest that lifetime extension will not alleviate the overall balance between material requirements and potential secondary supplies, but it could mitigate the potential supply bottlenecks and the needs for recycling infrastructure by reducing throughputs of materials.

The model was rerun for each parameter of lifetime function and each coefficient of empirical regressions, where one input was moved while keeping others fixed. Results regarding fiberglass flows under the Wind Scenario are selected to demonstrate the impacts of uncertainties in each parameter on simulation outputs. Results on other scenarios and other materials are documented in the Supporting Information. Figure 6c shows that the uncertainties in the exponent of the regression relationship between offshore wind turbines’ rotor diameter and nacelle weight affect the simulation outputs the most. If the exponent varies by ±76.00% (see statistical uncertainties in the Supporting Information), the inflow of fiberglass in 2050 will accordingly vary from 12.99 kt yr$^{-1}$ to 23.56 kt yr$^{-1}$, which is equivalent to [-19.37%, +48.68%]. Meanwhile, the outflow of fiberglass in 2050 will accordingly vary from 4.69 kt yr$^{-1}$ to 7.50 kt yr$^{-1}$, which is equivalent to [-15.70%, +38.75%].

These model and uncertainty analysis results confirm that considering bottom-up engineering data of technologies (e.g., the size scaling effect) in MFA could improve our understanding of materials requirement and implications with improved precision. Such a modeling framework could be applied to
wind energy development in other countries or regions and other emerging technologies (e.g., electrical vehicles, solar panels, and energy storage devices) that bear similar size scaling effects. Although incorporating size scaling effects is already one step forward, understanding the materials distributed in each individual component (e.g., fiberglass employed in blade or nacelle) could provide more nuanced information regarding component-level supply risks or secondary material availability, which requires future work on more detailed LCI data at the component level.

Using Denmark as an example, we presented a prospective model that incorporates the micro-engineering parameters, delivering a comprehensive assessment of the materials demand and secondary supply potentials of wind energy development. Our results signaled that Denmark’s ambitious transition towards 100% renewable energy will be facing increasing challenges of materials provision and end-of-life management in the next decades. We believe unlocking the material-energy-emission nexus, as we show in this study, can eventually help understand the synergies and trade-offs of relevant resource, energy, and climate strategies and inform governmental and industry policy making in future renewable energy and climate transition.
**Figure 6.** a) Impacts of increasing market share on annual neodymium flows from 2018 to 2050 in the Hydrogen, IDA, Wind, Fossil, Biomass, and Biomass+ scenarios; b) Impacts of lifetime extension on cumulative neodymium flows from 2018 to 2050 in the Hydrogen, IDA, Wind, Fossil, Biomass, and Biomass+ scenarios; and c) Impacts of uncertainties in parameters of lifetime function and coefficients of empirical regressions on fiberglass flows under the Wind scenario. Dashed lines represent the baseline values of inflows and outflows; solid lines represent the simulation outputs of the one-factor-at-a-time sensitivity analysis on 22 parameters or coefficients.

**ASSOCIATED CONTENT**

The Supporting Information is available free of charge on the ACS Publications website at DOI: XXX. Supporting Information 1 includes additional figures and tables that support the modeling and the result interpretation. Supporting Information 2 includes results by onshore and offshore, additional results of the sensitivity analysis, and a prototype model that can be further adapted.

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