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Savings potential for material requirements through repowering in the German wind power expansion

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ABSTRACT

Germany's wind power sector faces increasing pressure from aging fleets and ambitious expansion targets. Repowering could curtail the primary material demand through reusing components. This study employs a dynamic material flow analysis from 1988 to 2050 to quantify resource requirements for capacity expansion to evaluate the material-saving potential of repowering. The results show that the extent of reuse in repowering is a primary lever of material efficiency. Repowering without reuse accelerates material throughput and results in the highest cumulative demand. Strategies that deepen the extent of reuse yield substantial material savings. In the offshore sector, reusing infrastructure and using modern turbines reduces demand for concrete, copper, and polymers by 11–15 %. Onshore, partial repowering proves most effective, lowering aggregate demand for copper, steel, and aluminum by 7–14 %. Consequently, stakeholders should prioritize partial, reuse-intensive repowering pathways to balance capacity expansion, area efficiency, and resource conservation.

1. Introduction

Germany, a pioneer in wind energy, stands among many nations challenged by the European Green Deal and its objective of achieving climate neutrality. With a 33 % share of total net electricity generation, wind power already plays a central role in Germany's energy transition (Fraunhofer ISE, 2024). Considering the targets set in the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG), wind power growth must continue over the coming decades (EEG 2023, 2014). While the energy transition hinges on economic analyses and technological advancements, it cannot be achieved without accounting for resource demand and potential supply bottlenecks (Shammugam et al., 2019). Global ambitions towards clean energy significantly increase resource demand for metals and minerals in the energy sector, raising concerns around the reliability and sustainability of material supply (IEA, 2021). For this reason, identifying potential material savings in a resource-focused analysis is a precondition for Germany's capacity-expansion ambitions. Further challenges include the aging of wind turbines in operation, which necessitate replacement efforts once these systems reach their end-of-life (EoL). Therefore, Germany is confronted not only with its set expansion goal but also with the need to replace wind turbines that will fall out of commission.

Technological advancements have led to larger rotor diameters, higher hub heights, and greater rated power for wind turbines, as well as increased use of permanent magnets and, therefore, rare earth elements (REEs). The ambition for larger, more efficient models and the growing number of aging wind turbines in operation underscore the need for repowering. Repowering is the process of replacing outdated wind turbines with more advanced models to increase site capacity and efficiency (Ahmed et al., 2024; Grau et al., 2021). The wind energy sector benefits from repowering through streamlined permitting processes (Madlener et al., 2019). Wind farm operators also profit from the advantage of utilizing existing wind sites, which are already equipped with essential infrastructure, grid connections, energy production licenses, and historical performance data (Ahmed et al., 2024). However, reusing wind sites not only optimizes land use but also enables the reuse of various components, thereby contributing to material efficiency.

Both repowering projects and new installations aim to fulfill Germany's wind power capacity expansion targets within the energy transition. At the same time, repowering projects and new installations both require substantial resource input. Market tightness poses the risk of slowing down the energy transition. Permanent magnets deployed in synchronous generators of wind turbines create significant dependencies for EU countries, as they require rare earth elements (REEs) such as neodymium and dysprosium. China dominates the REE value

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chain, including magnet production (IEA, 2021). While 85 % of processed neodymium is sourced from China, the dependency on China for processed dysprosium rises to 100 % (Carrara et al., 2025). Material quantification of future projections on wind energy deployment reveals requirements, bottlenecks, and the potential of strategies for efficient resource use. Shammugam et al. (2019) and Zimmermann et al. (2013) determined future material flows in the German wind energy sector under different capacity-growth and technological-development scenarios. Their findings highlight that a substantial increase in capacity leads to significant primary material demand and supply pressure that needs to be mitigated through material efficiency and secondary material recovery. Studies at the national level on Denmark (Cao et al., 2019), Sweden (Savvidou and Johnsson, 2023), and Canada (Jiang et al., 2025) similarly concluded that recycling and improved material intensity are essential to limit pressure on primary material demand under capacity expansion pathways. Li et al. (2022) mapped global future material and energy flows, while the European Commission identified trends and criticalities in material demand for the EU, and globally (Carrara et al., 2020). Both concluded that REE supply constraints can potentially limit the pace of the energy transition and highlighted the importance of demand-reducing strategies such as lifetime extension, material efficiency, or substitution. In a study of wind turbine circularity potential, Gast et al. (2024) analyzed the impact of material recovery, reduction, recycling, and reuse on the turbine level using a circularity index. They identified recycling and component reuse as promising strategies to reduce the material demand and emphasized the need for active collaboration with key stakeholders to enhance the feasibility and implementation of these strategies. For France, Tazi et al. (2019) quantified EoL material flows from past installations and stressed uncertainties related to lifetime assumptions and recyclability rates, calling for improved end-of-life planning. At the European level, Lichtenegger et al. (2020) identified geographic and temporal hotspots for circular economy pathways for wind turbine blade waste. A Swedish study found a need for expanded recycling capacity and improved dismantling practices to handle the rising volume of waste in the future, while proposing strategies to extend the service life of wind turbine components to mitigate future waste burdens (Andersen et al., 2016). For Australia, Alavi et al. (2024) projected that concrete, steel, and composites will dominate the cumulative waste streams from wind turbines and identified repowering as a potential waste-reduction strategy for concrete and steel.

While these studies consistently demonstrate the scale and management challenges of future decommissioning waste as well as the material demand pressure from capacity expansion in energy transition, the quantitative impact of repowering on cumulative material demand and as a strategy for component reuse has yet to be analyzed. Using a dynamic material flow analysis (dMFA), the material demand of Germany's energy transition ambitions in the wind energy sector is determined under different repowering scenarios. To our knowledge, these scenarios are the first to effectively isolate the extent of component reuse as a variable in wind farm repowering. The study aims to find how cumulative resource requirements can be reduced while supporting Germany's wind capacity expansion through strategic repowering. The research question guiding this study is defined as follows:

What is the minimum resource requirement for achieving the capacity expansion targets for wind power in Germany, considering new installations and repowering?

To address this, the study combines site-specific, high-resolution historical capacity data with empirical scaling relationships and technology developments to model material flows for onshore and offshore wind power under future repowering and new installation scenarios in Germany over the period 1988 to 2050. It explicitly assesses the feasibility of component reuse in repowering by incorporating technological constraints, component lifetimes, and spatial requirements into the scenario design and dynamic modelling. The analysis extends beyond turbine-level assessments by accounting for material demand and the reuse potential of wind farm infrastructure components.

2. Data and methodology

2.1. Scope and system boundary

The scope of this study encompasses the entire system, from wind turbines that generate energy to the grid connection. This includes the turbines and their four main components: foundation, tower, nacelle, and rotor, as well as all components that are part of the wind farm infrastructure. It comprises site cables, switchgear, and transformers for onshore wind farms, whereas offshore wind farms require array cables and export cables, as well as an offshore and an onshore substation. Fig. 1 presents an overview of the components considered and their respective technological variants.

Wind turbines vary in drivetrain configuration and tower type. The technological variants are chosen for the model based on their market dominance. This study differentiates between two geared systems, the Double-Fed Induction Generator (DFIG) and the Permanent Magnet Synchronous Generator with Gearbox (PMSG-GB), as well as two direct-drive systems, the Electrically Excited Synchronous Generator Direct-Drive (EESG-DD) and the Permanent Magnet Synchronous Generator Direct-Drive (PMSG-DD). Two tower types, the tubular steel tower and the concrete tower, are selected. While the flat base foundation for onshore turbines remains unrivaled, the monopile structure for offshore turbines was chosen, consistent with its market lead of 60 % globally (DOE, 2023). This study selects materials that together constitute over 95 % of the mass of both the wind turbine and the wind farm. Structural materials include concrete, steel, aluminum, copper, polymers, and composites, while neodymium and dysprosium are classified as critical materials. The selection in this study focuses on materials that dominate total mass, structural function, or criticality concerns, to ensure that the analysis captures the most significant contributors to resource use. While other materials such as zinc for coating, or chromium, nickel, manganese, and molybdenum as alloying materials in steel are also present in wind turbines (Li et al., 2022), they are omitted from the scope as they contribute relatively small mass fractions, and the available life cycle inventory (LCI) datasets were not sufficiently granular to isolate and quantify these materials reliably. The system boundaries include Germany over the period 1988 to 2050. 1988 is the year of installation of the first turbine that fully supplied its electricity to the grid and had a rated power of $>$0.05 MW. The year 2050 aligns with the ambitions of the European Green Deal to reach climate neutrality. Installations and decommissionings of historical years are derived from the official German register for all energy production and storage units, managed by the Federal Network Agency, called Market Master Data Register (in German "Marktstammdatenregister", abbreviated MaStR) (Bundesnetzagentur, 2025). The system variables in this study are characterized across multiple aspects presented in the Supplementary Information. The model developed in this study is adaptable for applications in other countries, provided sufficient data on the existing wind fleet is available. The model requires information on turbine locations, ages, configurations, and wind-farm allocations. High-resolution regional wind power density data are needed to calculate the site favorability index for the specific country of application. By replacing these inputs for Germany with analogous datasets from other regions, the framework can estimate material demand for new installations and repowering under country-specific capacity trajectories.

2.2. Model overview

This study integrates capacity requirements and material composition into a stock-driven dynamic material flow analysis (dMFA) model. Fig. 2 visualizes the calculation flowchart. Flows in a dMFA indicate how materials enter, circulate, and leave a defined system, thereby changing in quantity and distribution (Müller et al., 2014). In the stock-driven

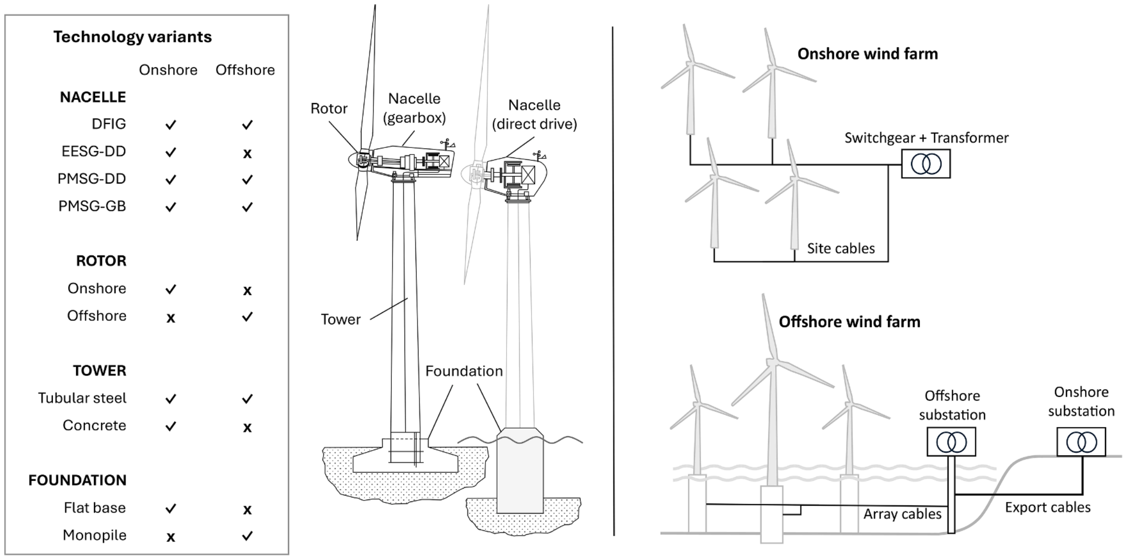

Fig. 1. Technology variants and system components for onshore and offshore wind turbines and wind farms.

approach, outflows are determined by the lifetimes of wind turbines or wind parks. Inflows iteratively adjust the stock to a target stock level derived from a service demand for each time step (Pauliuk and Müller, 2014). In this model, the annual addition of wind power capacity ("inflow") and the annual decommissioning of capacity ("outflow") depend on turbine and wind farm lifetimes, repowering activities, and expansion requirements to achieve the mandated wind power capacity ("stock"). Capacity flows are converted into material flows using material composition calculation and dynamic archetype turbine modeling. Throughout the study, repowering is abbreviated as "RP" and new installations as "NI".

2.3. Capacity flows

The information required for calculating historical capacity flows comprises rated power, location, and the years of installation and decommissioning for each turbine, all of which can be extracted from the MaStR.

The capacity stocks are determined by the mass balance principle as the difference between total installed capacity and total decommissioned capacity. In the stock-driven modelling approach, the stock represents the desired service demand. The year 1988 marks the first year of stock accumulation. The stock before that year is assumed to be zero.

Capacity requirements are calculated endogenously to satisfy the target stock after accounting for outflows:

$$\mathrm{CI}(t) = \mathrm{CS}_{\mathrm{target}}(t) - \mathrm{CS}(t-1) + \mathrm{CO}(t) \quad (1)$$

Where $\mathrm{CI}(t)$ represents the capacity installations in year t, $\mathrm{CS}_{\mathrm{target}}(t)$ corresponds to the exogenously defined target capacity stock in year t, $\mathrm{CS}(t-1)$ is the installed capacity stock in the previous year, and $\mathrm{CO}(t)$ denotes the capacity outflow in year t. This ensures that annual installations compensate for decommissioned capacity and provide the additional expansion required to reach the prescribed capacity expansion goals.

All turbines from the pre-existing fleet before 2025, future repowering projects, and new installations are tracked by age cohort to calculate the annual capacity development. To preserve their heterogeneous size and configuration, existing turbines are characterized by unit-specific attributes within their respective cohorts. Future turbines are assigned cohort-specific archetype characteristics. An annual cap of 12 GW on capacity additions is introduced to avoid overestimating yearly installation efforts based on the auction volume proposed by the German government (WindEurope, 2022).

The onshore and offshore capacity stock is updated each year from 2024, accounting for decommissioning, repowering, and new installations:

$$\mathrm{CS}(t,r) = \mathrm{CS}(2024,r) + \sum_{\tau=2025}^{t}\Big(- \mathrm{C}_{\mathrm{Dec,fut}}(\tau,r) - \mathrm{C}_{\mathrm{Dec,orig}}(\tau,r) + \Delta\mathrm{C}_{\mathrm{RP}}(\tau,r) + \mathrm{C}_{\mathrm{NI}}(\tau,r)\Big) \quad (2)$$

$\mathrm{CS}(t,r)$ corresponds to the future capacity stock in a year t and region r starting from an initial capacity stock $\mathrm{CS}(2024,r)$ of 61.2 GW onshore and 8.3 GW offshore. $\mathrm{C}_{\mathrm{Dec,fut}}(\tau,r)$ is the capacity of turbines installed in a past year τ as part of repowering events or new installations, and $\mathrm{C}_{\mathrm{Dec,orig}}(\tau,r)$ represents the capacity outflow from pre-existing turbines in the wind fleet that are not feasible for repowering. $\Delta\mathrm{C}_{\mathrm{RP}}(\tau,r)$ are additions of scenario-dependent capacity gains through repowering and $\mathrm{C}_{\mathrm{NI}}(\tau,r)$ is the newly installed capacity.

2.4. Scenario assumptions

All scenarios aim to fulfill the service demand set by the German federal government in pursuit of climate neutrality by 2050. By 2026, onshore wind capacity is projected to reach 84 GW, rising to 88 GW by 2028. The targets for 2030, 2035, and 2040 are set in § 4 of the EEG at 115 GW, 157 GW, and 160 GW, respectively, beyond which capacity should be maintained at that level (EEG 2023, 2014). As defined in § 1 of the Offshore Wind Energy Act (Windenergie-auf-See-Gesetz, WindSeeG), offshore wind is set to reach 30 GW in 2030, increase to 40 GW in 2035, and maintain a steady level of 70 GW from 2045 onwards (WindSeeG, 2016). These expansion goals are the exogenous service demand to perform stock-driven modelling. Existing trajectories for the German energy transformation, such as those developed within the Ariadne project, forecast onshore wind capacities of 160–214 GW and offshore wind capacities of 57–70 GW by 2045 across multiple energy system models with only moderate variation to other transformation scenarios (Luderer et al., 2025). They concluded that renewable capacity expansion, at least at the level of current policy targets, is essential to achieve climate neutrality. The capacity expansion assumptions in this study are therefore both policy-consistent and placed within the range of existing forecasts for German wind power development. Table 1 outlines the four different future repowering and new installations scenarios of this study. Under a material perspective, repowering holds the advantage of reusing components for the wind

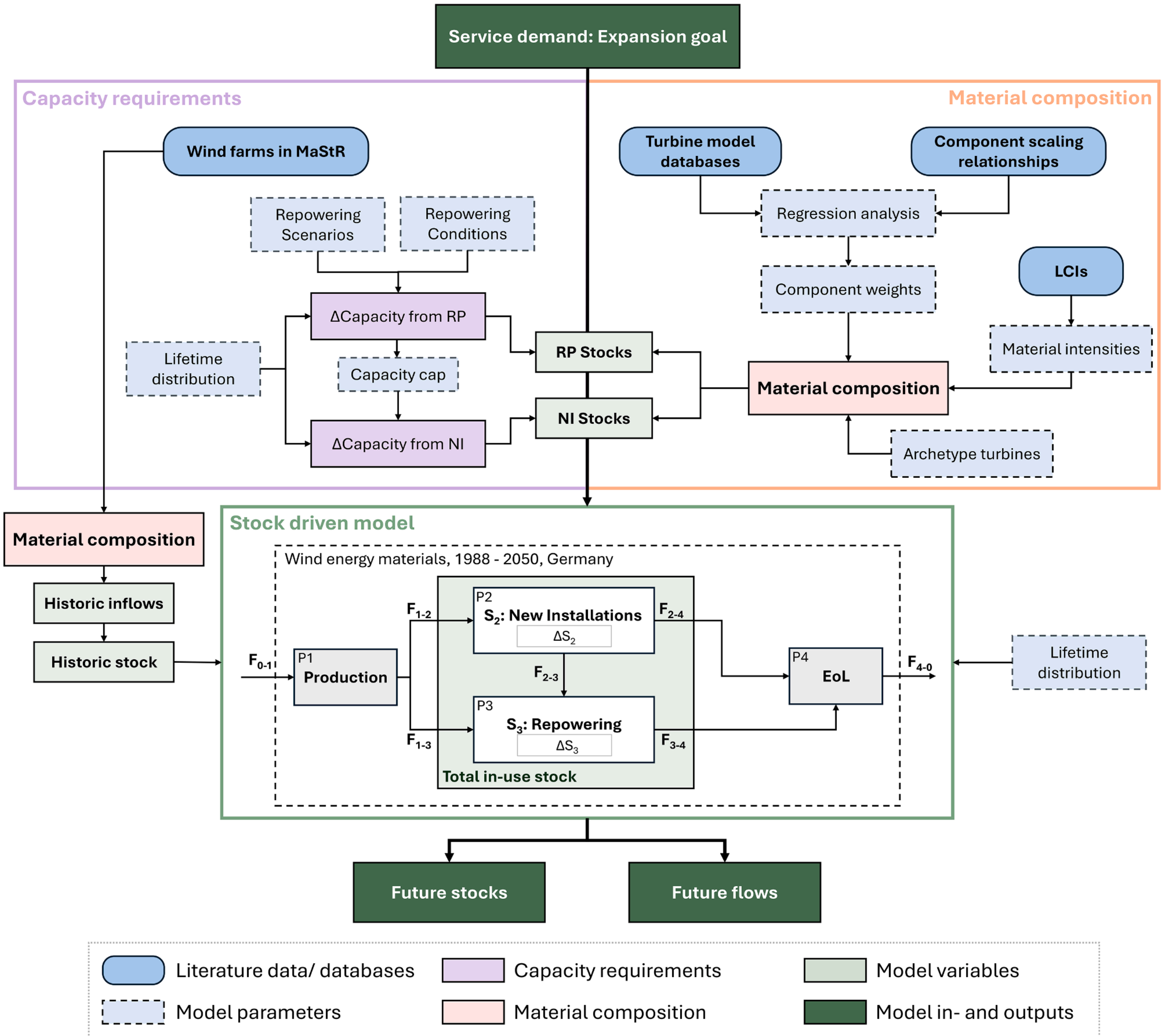

Fig. 2. Flowchart of the calculation process with all model components.

Table 1
Wind farm expansion and repowering scenarios with their respective component reuse potential.

Scenario	Wind farm capacity	Goal	Quantified reuse potential
S1	2 x capacity	Maximizing wind exploitation per area through repowering	-
S2	1.5 x capacity	Combining exploitation and resource efficiency in repowering	Transformers, switchgears, export cables, onshore substations, offshore substations
S3	1 x capacity	Maximizing the reusability potential of repowering	Towers, flat-based and monopile foundations, transformers, switchgears, site cables, export cables, onshore substations, offshore substations, array cables
S4	-	Expansion via new installations only	0 % of turbines repowered

farm upgrade. A turbine's lifetime is limited by load bearing, as wear and fatigue influence stability and performance. The wind turbine manufacturer Vestas recognizes that components not exposed to strong wind forces or cyclic loads may have a significantly longer useful lifetime of up to 50 years (Vestas Wind Systems, 2024). Along with the component's design lifetime, its reusability in a repowering project also depends on its compatibility with modern turbine specifications and size.

Scenario 1 represents a business-as-usual scenario proposed by Bošnjaković et al. (2022), in which repowering doubles wind farm capacity by deploying modern turbines to maximize area-exploitation efficiency. The large capacity increase generally exceeds the design limits of substation components, preventing any reuse. Furthermore, modern turbines are larger and heavier, requiring redistribution of turbine positions within the wind farm due to spacing constraints. This rules out the reuse of existing foundations. Towers, rotors, and nacelles from the replaced turbines cannot be reused, as they neither fit the physical requirements to withstand the new loads nor the dimensional requirements of modern turbines.

In **scenario 2**, repowering increases wind farm capacity by 1.5 times through deploying modern turbines. According to Martínez et al. (2018) and Siemens Energy (2021), infrastructure components are over-dimensioned and capable of withstanding moderate capacity increases. Aligning with their statements, it is assumed that wind farm infrastructure does not need to be replaced for a 50 % capacity increase, allowing the reuse of switchgear and transformers in onshore wind farms, as well as export cables and offshore and onshore substations in offshore wind farms. Turbine-specific components cannot be reused, as turbine spacing and size constraints prevent integration of replaced components with modern turbine models, similar to scenario 1.

Scenario 3 aims to maximize the reuse potential through partial repowering. Partial repowering replaces the rotor and nacelle of eligible turbines while reusing the remaining turbine and infrastructure components (IRENA, 2019). Eligibility is limited to onshore turbines with a rated power above 2 MW and offshore turbines with a rated power above 4 MW. This ensures that the required components for partial repowering are reflected by the product portfolios of key market players and can be produced in the current and future manufacturing landscape. Turbines below that threshold are decommissioned and any resulting capacity gap at a wind farm level is backfilled by modern turbines. A wind farm is suitable for repowering if one or more turbines are over the eligibility threshold. In this scenario, all components of the turbine and wind farm infrastructure can be reused except the rotor and nacelle.

Scenario 4 is modeled without repowering as an option. All capacity expansion is achieved solely through new installations. Since no turbines are repowered, there is no potential for component reuse.

In each scenario, the repowering feasibility of individual wind farms is determined dependent on the aforementioned scenario-dependent constraints. The model first upgrades capacity through repowering wherever feasible, and any remaining capacity required to meet the annual expansion goal is added via new installations. Because repowering is determined dynamically based on the existing fleet and site characteristics, the proportion of repowered versus newly installed turbines varies between scenarios and over time.

2.5. Lifetime assumptions

The Weibull distribution is widely applied in the context of wind turbine lifetime (e.g., Cao et al., 2019; Jiang et al., 2025; Zimmermann et al., 2013). While the design lifetime of onshore turbines is set to 20 years (IRENA, 2019), their mean lifetime in Germany, based on real-world decommissioning data, is estimated at 22.6 years (Quentin, 2025). For offshore turbines, their design lifetime of 25 years (Vestas Wind Systems, 2024) was used due to the lack of decommissioning data in the offshore wind power sector. A shape factor of 4 was assumed for both onshore and offshore turbines based on Cao et al. (2019). Decommissioning of individual turbines that are not repowered is modeled using a Weibull distribution. A turbine is decommissioned if repowering is not feasible for the wind farm, the turbine is older than 30 years, or the scenario does not account for repowering.

Repowering timing is determined at the wind-farm-level. This means that the year of repowering applies to all turbines in a wind farm, while in non-repowered wind farms, turbines are decommissioned based on their individual residual lifetimes. For wind farms eligible for repowering, the model shifts from Weibull to a beta distribution applied at the wind-farm level. Using a beta distribution allows for a repowering probability modelling within a deterministic window. The optimal economic repowering time for onshore wind farms is 15 years of age based on operation and maintenance costs, load factor decline, and EEG feed-in tariffs (Madlener et al., 2019). The modal repowering age of 18 years for onshore and 20 years for offshore wind farms is chosen. It reflects an intermediate point between the economic optimum and the statement from WindEurope of repowering at design EoL (WindEurope, 2023). Based on Madlener et al. (2019), it is assumed that repowering is not considered an option from an economic perspective before 10 years and after 30 years. The oldest wind turbine in the wind farm determines the wind farm's age. A site-favorability index (SF) was developed to prioritize the best sites for wind turbine installation in repowering projects. This index is based on wind power density, which indicates available energy at a site for conversion to electricity by a wind turbine (Katinas et al., 2018). Detailed calculations of the SF are explained in the Supplementary Information. A low SF can shift the repowering mode year to a maximum of 25 years, reflecting the industry's tendency to repower economically attractive sites first.

2.6. Material composition

Along with capacity, wind turbines grow in rated power, rotor diameter, and hub height. Turbine upscaling prevents the use of fixed material-intensity values, since the mass of turbine components does not scale linearly with increasing rated power. Empirical scaling relationships for the foundation, tower, rotor, and nacelle are derived from Caduff et al. (2012). They propose proportionality between component weight and rotor diameter for the rotor, nacelle, and foundation, while the tower weight (m_{Tower}) increases with the product of the rotor diameter squared and the hub height. This accounts for the loads on the tower based on its height and the dynamic wind forces with increasing rotor swept area. The power law (Caduff et al., 2012) calculates component weights:

$$m_{component} = a \cdot x^{b} \tag{3}$$

Where a is the intercept factor, b is the scaling factor, and x is the component-specific scaling variable. To perform linear regression, component weight data are obtained from the two turbine model databases, The Wind Power (The Wind Power, 2025) and Wind-Turbine-Models (Wind-Turbine-Models, 2025), and multiple Life Cycle Inventories (LCIs) from the literature. The Supplementary Information provides a complete list of LCI references and regression plots of all turbine components in their technological variants. Intercept and scaling factors for the components and their technology variants are listed in Table S5 of the Supplementary Information.

The LCIs provide material shares of the components. An analysis of material use by size reveals no significant trend in material composition with increasing rotor diameter. Average material shares are calculated and can be obtained from Table S6 in the Supplementary Information. Materials or components that are not sufficiently covered in the collected LCIs are modeled after literature values. Data gaps in material shares are filled for offshore rotors (Deutscher Bundestag, 2023) and the PMSG-DD and PMSG-GB nacelles (Shammugam et al., 2019). The monopile foundation is modeled after the Vestas offshore model "V236–15 MW" (Vestas Wind Systems, 2024). Material intensities for neodymium and dysprosium are obtained from JRC (2020). The rotor of a turbine is composed of composites and steel. Nacelles contain mostly steel, with copper, aluminum, polymers, and composites in smaller amounts. REEs are used primarily in the permanent magnets of the turbine generator, with minor quantities in magnetic mounts within the tower that replace bolted connections (Carrara et al., 2020). For this reason, they are also found in small amounts in DFIG and EESG-DD turbines, as listed in Table S7 (Supplementary Information). Tubular steel towers are steel structures with small amounts of aluminum, copper, and polymers, while concrete towers contain mostly concrete reinforced with steel, with minor shares of copper and polymers. Monopile foundations are made of steel, whereas flat-based foundations are made of concrete and steel.

Since infrastructure components are not exposed to wind forces, it is assumed that they scale linearly in accordance with Caduff et al. (2012), allowing for the use of material intensities. Averages are derived from 25 wind farm Life Cycle Assessments published by Vestas (Vestas Wind Systems, 2024) and displayed in Table S8 of the Supplementary Information. Onshore site cables contain aluminum, polymers, copper, and composites, while switchgears are made from steel, copper, and polymers, and transformers from steel, aluminum, copper, polymers, and composites. Offshore array cables include steel, aluminum, copper, and polymers, whereas export cables are made from steel, copper, and polymers. Both onshore and offshore substations in offshore wind farms are composed of steel, aluminum, copper, polymers, and composites, with concrete present only in the onshore substation.

The material composition of a wind turbine of known size and configuration is calculated using material shares and intensities, as well as the scaling relationships:

$$\mathrm{TM_m}(\mathrm{d,h,p}) = \mathrm{ms_{rt,m}}\left(\mathrm{a_{rt}}\cdot\,\mathrm{d^{b_{rt}}}\right) + \mathrm{ms_{tt,m}}\left(\mathrm{a_{tt}}\cdot\,\left(\mathrm{d^2}\cdot\mathrm{h}\right)^{\mathrm{b_{tt}}}\right) + \mathrm{ms_{ft,m}}\left(\mathrm{a_{ft}}\cdot\,\mathrm{d^{b_{ft}}}\right) + \mathrm{ms_{nt,m}}\left(\mathrm{a_{nt}}\cdot\,\mathrm{d^{b_{nt}}}\right) + \mathrm{MI_{nt,m}}\cdot\,p + \mathrm{MI_{ct,m}}\cdot\,\mathrm{p} \tag{4}$$

In this study, p denotes the rated power of an individual turbine, whereas P represents the total capacity of a wind farm. The turbine material composition $\mathrm{TM_m}$ requires information on rotor diameter d, hub height h, rated power p, and a technological variant for the rotor (rt: onshore; offshore), nacelle (nt: DFIG; EESG-DD; PMSG-GB; PMSG-DD), tower (tt: tubular-steel; concrete), foundation (ft: flat base; monopile), and cables (ct: site cable; array cable to be calculated. The mass share $\mathrm{ms_m}$ of material m in a component is multiplied by the component weight obtained through the respective scaling and intercept factors. $\mathrm{MI_m}$ is the material intensity per MW, which is available for the cables as well as the REE contents in the turbine, dependent on the nacelle variant. Site cables and array cables are included since they connect each turbine to the residual wind farm infrastructure. The material composition of the wind farm infrastructure is determined using material intensities and wind farm capacity:

$$\mathrm{WFM_m} = \sum_{\mathrm{g}\in\mathrm{G(it)}} \mathrm{MI_{it,\ g,m}}\cdot\,\mathrm{P} \tag{5}$$

Where $\mathrm{WFM_m}$ corresponds to wind farm material composition, and MI are the material intensities. The components are selected based on infrastructure technology (it: onshore; offshore). G(onshore) includes switchgear and transformer, whereas G(offshore) comprises offshore substation, export cable, and onshore substation.

2.7. Translation of capacity flows into material demand

Translating capacity flows into material demand requires projections of future turbine sizes and market share developments. The future turbine models are labeled as archetypes. The developments in rated power, rotor diameter, and hub height, as well as market shares of the technology variants for drivetrain and tower, are based on product portfolios from key manufacturers and predictions from industry reports. The assumed future size and configuration trajectories are outlined in further detail in the supplementary information. Announced, but not yet commissioned turbines average at 5.6 MW for onshore and 13.0 MW for offshore in the MaStR. This serves as the starting point for the archetype turbine modelling and is consistent with projections by IRENA (2019) for global developments, as well as with German-focused analyses by WindGuard for onshore (WindGuard, 2025a) and offshore (WindGuard, 2025b). The average turbine size for the years up to 2035 is projected to align with next-generation turbine models in the product portfolios of key manufacturers, ranging from 6 to 7.2 MW onshore and 12 to 15 MW offshore. By 2050, the rated power of onshore turbines will reach 9 MW. This assumption is based on onshore turbine models that are currently available or under development, as listed in the turbine model databases “The Wind Power” and “Wind-Turbine-Models”. Offshore turbine capacities are projected to grow to 18 MW (WindGuard, 2025b). Trajectories for future rotor diameter and hub height are estimated using regression models that capture their correlation with rated power, based on data from the MaStR and the two turbine model databases.

While tubular steel towers remain the only option for offshore turbines, concrete towers are gaining momentum as turbine height rises, increasing their share from 10 to 30 %. This assumption stems from the limitation on the tower section diameter imposed by the vertical clearance of German road bridges (Alvarez-Anton et al., 2016). The onshore drivetrain market will remain dominated by DFIG, with a modest decline from 60 % to 50 % during the modelling timeframe, due to its independence from REEs and manufacturers’ long-term operating experience (Shammugam et al., 2019). The EESG-DD share is assumed to decline by 3 %, attributable to its substantial weight gain for high-rated turbines (Månberger and Stenqvist, 2018). PMSG technologies show an upward trend from 16 % to 20 % for PMSG-DD and from 11 % to 20 % for PMSG-GB, as their power yield and reliability rank highest among the other technological variants (Desalegn et al., 2022). In the offshore sector, the study predicts a significant increase in PMSG-DD market share from 20 % to 70 % due to its efficiency. Maintenance requirements put geared designs at an economic disadvantage in offshore applications (Desalegn et al., 2022). For that reason, this study assumes a complete phase-out of DFIG and reduces the PMSG-GB's share to 30 % by 2050.

3. Results & discussion

3.1. Historical stock and flows

Policy incentives such as changes in funding or subsidies have been a driver of Germany’s onshore and offshore wind energy sector, leading to installation peaks in the past. In 2024, onshore wind power reached a cumulative capacity of 61.3 GW, and offshore wind accounts for 8.3 GW in operation. While individual turbines were dismantled as early as 2009 or 2013, large onshore outflows began in 2019 (91.1 MW). These outflows correspond to the installation peak in the early 2000s, indicating that decommissioning will increase in the upcoming years. Offshore wind power development began around 2009, approximately a decade after onshore wind was successfully established as a renewable energy source. Given the sector’s young age, no offshore turbines have been dismantled yet. The development of onshore and offshore wind capacity is presented in Figure S16 (Supplementary Information).

Capacity installation peaks are mirrored in the material flow calculations. Fig. 3 shows the development of the in-use material stocks from 1988 until 2024 for each material in the onshore and offshore wind energy sector and highlights the material stock in 2024.

3.2. Future capacity flows

The simulation assesses wind farms suitable for repowering and their resulting capacity additions, identifies sites for decommissioning rather than repowering, and covers the remaining capacity needed each year through new installations, capped at 12 GW annually. The two lifetime models create different timeframes for repowering and decommissioning. While the Weibull distribution leads to a long-tailed decommissioning period, with an average of 22.6 years (offshore: 25 years), the beta model for repowering concentrates the probability of outflow into a more peaked distribution, with a mode of 18 years (offshore: 20 years). As a result, repowering, on average, is performed before the turbine’s EoL, leading to turbines exiting the use-phase several years earlier when repowered. This difference is visualized in Figure S19 of the Supplementary Information, which compares the two lifetime models under the assumption that all wind farms are either repowered or all turbines are decommissioned, exemplified for onshore wind capacity.

Within each scenario, the repowering and decommissioning of the pre-existing fleet vary depending on the scenario-specific repowering feasibility of wind farms. Fig. 4 illustrates capacity additions through repowering and new installations, as well as capacity removals due to repowering and decommissioning over the modelling timeframe in each scenario for onshore and offshore wind. In scenario 1, most wind farms qualify for repowering, resulting in the largest repowering activities and the largest associated outflows. The increase in capacity of existing wind farms through repowering in scenario 1 leads to the lowest need for new

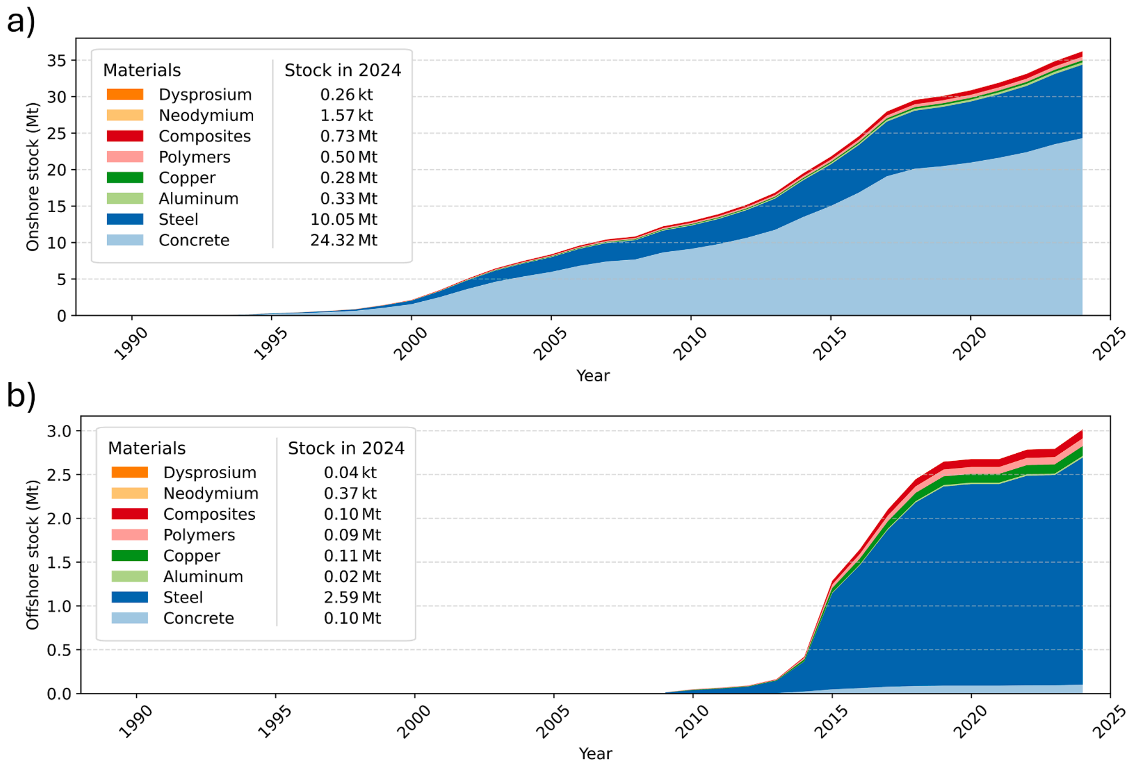

Fig. 3. Onshore (a) and offshore (b) material stock development until 2024.

installations among all scenarios and therefore minimizes land use for wind energy. Scenario 2 shows a similar but slightly lower effect. Since repowering occurs earlier and more rapidly than pure decommissioning, it generates larger outflows at the beginning of the modelling period. As a result, replacement needs arise sooner, putting additional pressure on the expansion targets. In combination with the 12 GW capacity-addition cap, the service demand cannot be fully met in scenarios 1 and 2 due to the high replacement effort. The targets will be reached in 2035, when the expansion speed decelerates. Onshore wind energy has reached a cumulative capacity of 157 GW by this time, marking the end of aggressive expansion and the beginning of fleet maintenance. For this reason, the additions to stocks through new installations are reduced across all scenarios.

All offshore wind farms are found to be feasible for repowering and are repowered in periods around 2030, 2035, and 2040. This clustering arises from repowering timing decisions at the wind farm level, where the larger scale of offshore wind farms leads to more synchronized repowering windows than in smaller onshore wind farms. At no point during the modelling time frame is repowering sufficient to meet the expansion goals. Therefore, all scenarios require substantial amounts of new installation, while scenario 1 necessitates the least new installation fields.

3.3. Future material flows

Across all four scenarios, the same service demand is met, but varying repowering activity changes cumulative demand by 2050. Fig. 5 displays the absolute material demand by 2050 for all materials, along with relative savings compared to the maximum scenario, for onshore wind energy. Scenario 3 yields the lowest material demand across all materials except for composites. Composites are required in rotor blades, which cannot be reused in either scenario. Since scenario 3 does not repower wind farms with modern turbines, but with models similar in size and configuration, the turbine technology landscape entails fewer PMSGs and therefore requires less neodymium and dysprosium. The most significant material savings in scenario 3 compared to the other scenarios are achieved for concrete, steel, aluminum, and polymers. Reusing the foundation results in a 14 % reduction in concrete compared to scenario 1. Through the reuse of towers, foundation reinforcement, and wind farm infrastructure, scenario 3 also saves 10 % in steel. Site cable, switchgear, and transformer reuse attribute to savings in aluminum (13 %), copper (7 %), and polymers (13 %). In scenario 2, the wind farm infrastructure is also reusable. Maintaining the copper-intensive transformer results in 12.65 kt copper savings compared to scenario 1. Across all materials, scenario 4 shows lower material demand than scenarios 1 and 2. This stems from the 4.6-year gap between the average repowering age and the average decommissioning age. In repowering, materials leave the use-phase earlier. Shortened lifetimes due to repowering require more turbine generations to cover the same time span in the modelling horizon. This ultimately results in increased material demand.

In the offshore wind energy sector, wind farm infrastructure is more material-intensive due to the need to transmit power to land through large cables and power inverters. Both towers and monopile foundations are primarily made from steel and can be reused in repowering in scenario 3, leading to an 8 % saving compared to scenario 1. While the reuse of towers, foundations, cabling, and onshore infrastructure results in scenario 3 having the lowest demand for most materials, this outcome does not hold for offshore wind. Concrete, copper, and polymers are used in wind farm infrastructure. For these materials, scenario 2 holds the lowest requirements. Scenario 2 allows for reusing the material-intensive substations and export cables over an increased site capacity of 50 %. While scenario 3 reuses the same components, the lack of site densification of capacity results in more new installations being required to meet the expansion goals than in scenario 2. For composites, scenario 4 shows the lowest demand, proving that without reuse, the scenario that keeps materials in use longer, yields the least demand over the modelling timeframe. For neodymium and dysprosium, the effect of a changed technology landscape under scenario 3 results in lower demand than in the other scenarios.

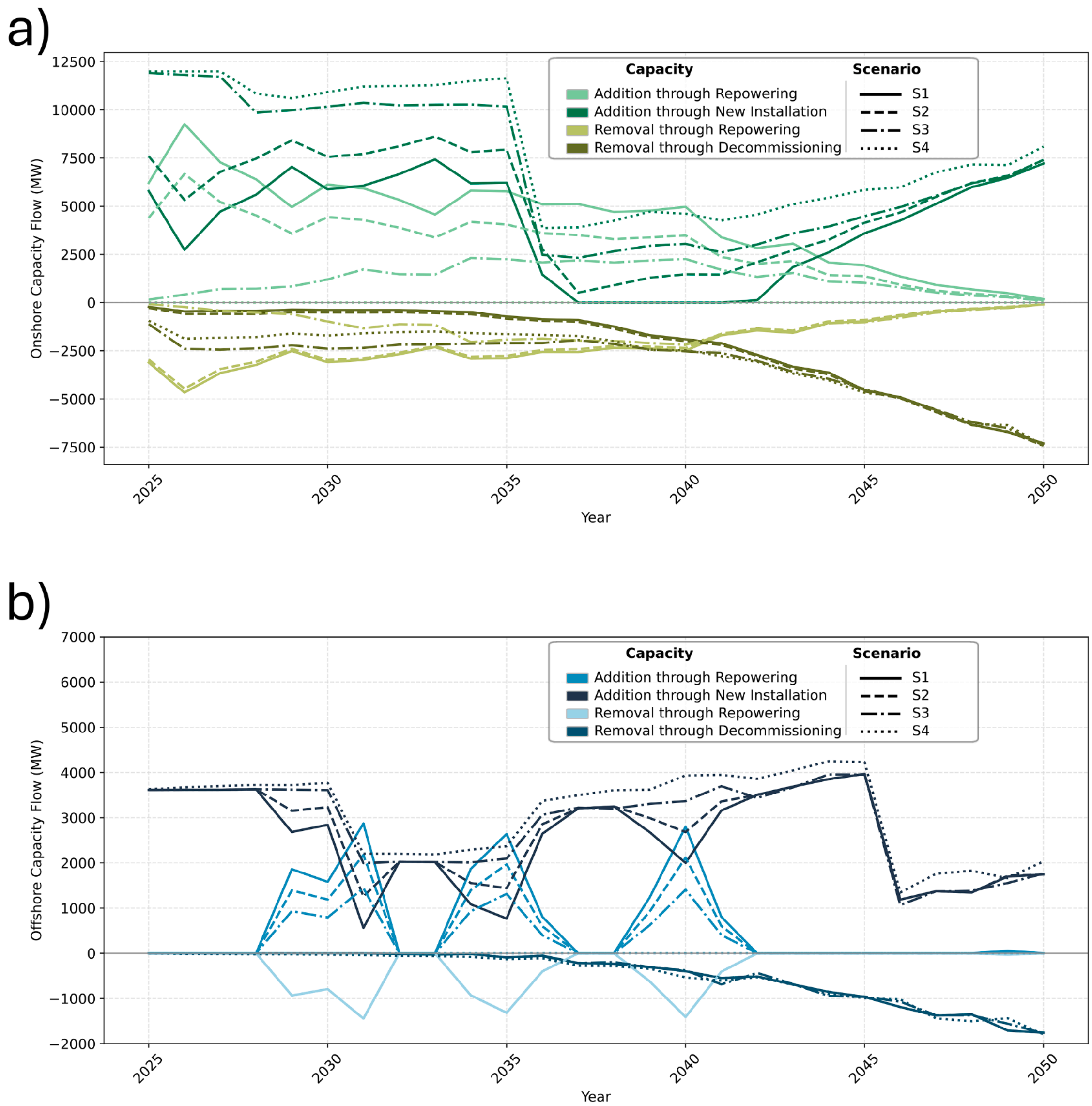

Fig. 4. Capacity additions and removals through repowering, new installation, and decommissioning for each scenario onshore (a) and offshore (b).

Three materials stand out when comparing absolute material demand between onshore and offshore wind energy, highlighting differences between the two sectors. Onshore capacity is projected to increase from 61.3 GW to 160 GW by 2050, while offshore capacity targets 70 GW, starting from 8.3 GW in 2024. Although the expansion goals for onshore wind are quantitatively higher, copper demand for offshore wind is higher across all scenarios. This results from copper-intensive cabling required in offshore wind farms, particularly for export cables. This emphasizes the material intensity of offshore infrastructure. While neodymium and dysprosium are not part of a region-specific component, their requirements are similar despite the capacity variance between onshore and offshore. This results from the differences in drivetrain technology between the two sectors. Offshore, the deployment share of PMSG-DD and PMSG-GB together reaches 100 % by the end of the modelling period, while onshore, non-PM technologies such as DFIG (50 %) and EESG-DD (10 %) still account for the majority.

4. Discussion and limitations

4.1. Interpretation of the results

The comparison of demand across scenarios, materials, and the onshore versus offshore sector reveals that the extent of component reuse is a primary driver of resource efficiency in repowering projects. Beyond the focus on the potential savings from reuse, the study offers additional insights into the timing and technological landscape of repowering.

Timing refers to the decision of replacing capacity proactively through repowering or reactively at the turbines' EoL. Repowering before EoL concentrates material demand for new turbine components into a shorter timeframe, thereby accelerating material throughput.

The technology landscape refers to the deployment share of different drivetrain configurations, particularly the increasing adoption of PMSGs in onshore and offshore wind energy. The drivetrain choice heavily influences the requirements of critical materials. The partial repowering in scenario 3, in which the drivetrain configuration of repowered turbines is retained even when the nacelle is replaced, reduces the demand for neodymium and dysprosium. Retaining the nacelle variant implicitly favors existing technologies, illustrating how partial repowering can alleviate pressure on rare-earth supply chains as an indirect consequence rather than the result of explicit technology selection.

This study shows that the extent of reuse in repowering projects is an important lever of material efficiency. Business-as-usual repowering (scenario 1) without reuse leads to the highest material requirements

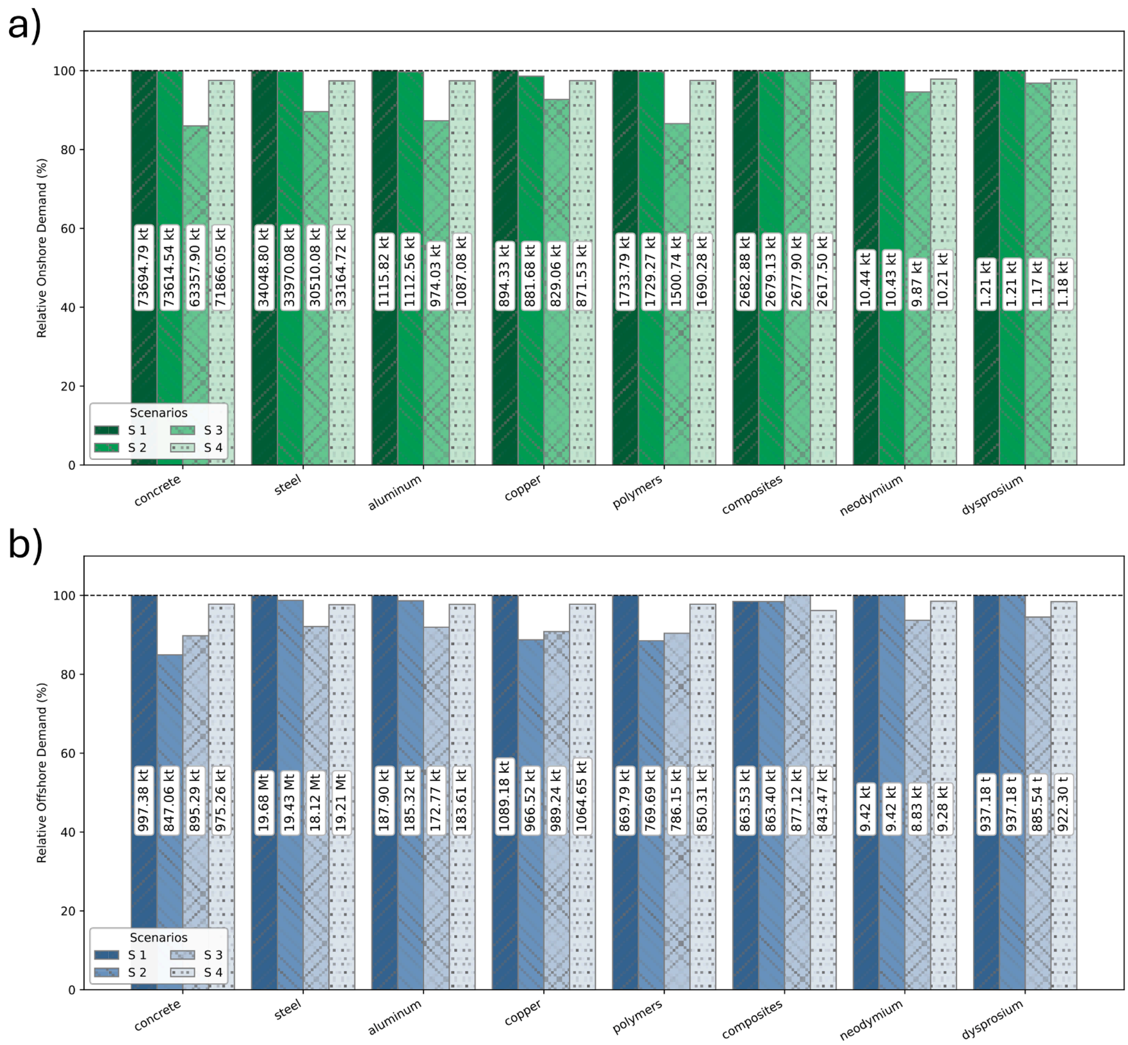

Fig. 5. Onshore (a) and offshore (b) material demands from 2025 to 2050 across all scenarios.

across all scenarios and materials. The results indicate that, from a material efficiency perspective, repowering without reuse performs worse than decommissioning turbines at their end-of-life and reconstructing the fleet from greenfield projects, as represented by scenario 4. This effect is visualized for each material, depicting the demand and waste over time across all scenarios. These figures illustrate the temporal dynamics of material flows within the system and are provided in the Supplementary Information (Figures S36-S51). Even though material cycles are shortened through repowering, reusing selective components yields substantial material savings. Scenario 2 retains the wind farm infrastructure. While this effect is only minor in onshore wind farms, the saving potential of infrastructure reuse becomes more apparent in offshore applications. This is because offshore wind farms require material-intensive infrastructures. Through an optimal trade-off between area and material use, scenario 2 in the offshore sector yields the lowest demand for concrete, copper, and polymers, saving 15 %, 11 %, and 12 %, respectively. Partial repowering (scenario 3) in the offshore wind sector shows similar, yet slightly lower, savings potential for these materials, but emerges as the most efficient strategy for steel and aluminum, saving 8 % for each material. Onshore, partial repowering offers the highest saving potential. By retaining foundations and towers alongside the wind farm infrastructure, partial repowering reduces demand for copper, steel, aluminum, polymers, and concrete by 7–14 %.

As this study shows, repowering is a dual mitigation lever. It enables technology and capacity upgrades to wind farms to effectively use high-quality sites. This is shown in scenario 1, where capacity is doubled through repowering. However, this also leads to higher material demand than in the other scenarios due to the absence of component reuse. Repowering can also serve as a circular economy strategy when implemented through component and infrastructure reuse. This is supported by scenario 3, where partial repowering effectively extends wind farm lifetimes, showcasing material savings through a high extent of reuse. This strategy aligns with the German Circular Economy Act (Kreislaufwirtschaftsgesetz, KrWG), which prioritizes waste prevention and aims to conserve natural resources by reducing the consumption of primary raw materials (KrWG, 2012). In summary, repowering focused solely on rapid capacity upgrades accelerates material demand, whereas reuse-intensive repowering significantly reduces material inputs but may limit capacity expansion at favorable sites. This suggests that policy frameworks should aim to align energy and resource objectives more explicitly. Rather than having contradicting effects, both capacity expansion and circularity through repowering can be combined into a synergistic mitigation strategy. Support schemes and permitting regimes could incentivize hybrid outcomes, for example, by integrating metrics that reward both capacity improvements and reuse intensity.

4.2. *Limitations and future research*

The objective of this study is to quantify material demand associated with capacity deployment in repowering and new installation projects for Germany, with a focus on wind power capacity rather than electricity generation. Capacity factors are partially addressed through a site-favorability index derived from regional wind power density, and through timing repowering informed by performance degradation and economic replacement thresholds. However, capacity factors are not explicitly modeled, introducing uncertainty because they influence turbine performance and repowering dynamics. Additional uncertainties stem from assumptions on the development of technology shares, hub heights, rated power, rotor diameters, lifetime distributions, and reuse opportunities for repowered components, as well as the omission of regulatory and procedural constraints such as multi-year repowering timelines and early repowering support schemes. Explicit consideration of capacity factors and these assumptions could provide refined insights into the timing and scale of repowering and its potential for component reuse, and consequently, projected material demand. A further limitation is that the analysis does not account for potential improvements in material efficiency or changes in material composition per component as turbine technologies evolve, which could influence overall material demand. Finally, the study applies scenario-based reuse potentials along capacity trajectories rather than a site-specific optimization. A more detailed, site-level approach could evaluate the benefits of reusing components to minimize material input and upgrading to modern turbines to maximize capacity and energy output, capturing the full potential of repowering in terms of both circularity and climate mitigation. Integrating such a site-specific decision framework represents a promising pathway for future research.

5. Conclusion

These insights are relevant for assessing and evaluating potential risks associated with material demand. Repowering emerges as a dual mitigation strategy, as it enables technological upgrading and capacity expansion at high-quality sites, while also offering substantial material savings when implemented in a reuse-intensive manner. Stakeholders are advised to leverage the repowering savings potential by considering repowering from a resource-use perspective. They should favor repowering designs that reuse components, where it is technically feasible, to avoid material-intensive scrapping before the technical EoL. To achieve further material savings, corresponding design improvements are needed. Non-load-bearing components can be constructed modularly, simplifying replacement or upgrades. By designing wind turbines and wind farm infrastructure specifically with repowering in mind, the reuse potential significantly increases. Due to the limited areas available for wind energy installations, repowering is inevitable for the German wind fleet. A trade-off among land use, reuse, and technology must be found to avoid constraints on area, resources, or supply in the wind energy sector. This study shows that this trade-off cannot be made solely on economic grounds but requires incorporating material reuse into repowering projects. From a policy perspective, expansion targets and circular economy objectives should not be treated as separate or competing agendas. Instead, repowering frameworks and policies should incentivize hybrid approaches that combine capacity improvements with reuse intensity. For stakeholders, this implies that repowering policies, project designs, and turbine concepts should aim for close-to-EoL, partial, and reuse-intensive repowering pathways to align wind power expansion with long-term resource efficiency.

CRediT authorship contribution statement

Riccarda Hieke: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Christoph Helbig:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Riccarda Hieke reports financial support was provided by Federal Ministry for Economic Affairs and Energy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2026.108981.

Data availability

Data will be made available on request.

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