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Assessing the circularity of onshore wind turbines: Using material flow analysis for improving end-of-life resource management

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ABSTRACT

Around 1,600 wind turbines are expected to be decommissioned annually in Germany after 2026. To reduce the amount of material going to landfills and minimise energy use, improving the circularity of decommissioned and new wind turbines is essential. However, there is currently limited understanding regarding wind turbine circularity and end-of-life component utilisation. To address this, this study examines the material flows of three 2-megawatt (MW) turbines in Germany and estimates their circularity using the Circularity Index proposed by Cullen (2017). This study finds low circularity in wind turbine material flows and suggests opportunities for improving resource management for a circular economy transition via enhanced component reuse and recycling. The authors also discuss options for using the Circularity Index and visualisations to monitor and enhance the circularity of renewable energy technologies and to identify opportunities for better resource management.

1. Introduction

Wind turbines contribute to the transition to low-carbon electricity systems. In the European Union, the installed capacity of onshore wind turbines is estimated to increase from 255 GW in 2022 to 384 GW in 2027 because of ambitious targets to reduce greenhouse gas emissions (WindEurope, 2022). These large quantities of wind turbines increase the demand for materials such as steel, concrete, and neodymium-iron-boron (NdFeB) permanent magnets, but also pose challenges for material reuse and recycling at end-of-life (EOL). Currently, wind turbines reach their EOL after 20 years or are dismantled even earlier to make space for newer and more efficient turbines (Jadali et al., 2021; Tazi et al., 2019). In 2020, more than 29,608 onshore wind turbines were installed in Germany and 203 turbines were decommissioned (Bundesverband WindEnergie, 2021). A study by Deutsche WindGuard (2016) estimated that there could be up to 1600 decommissioned wind turbines per year in the years following 2026. Dismantling wind turbines with up to 1000 tonnes of material is a complex process (Ortegon et al., 2013). At the same time, there are many challenges to EOL management; many of the blades (Liu and Barlow, 2017), up to 100 % of the concrete foundation (Garrett and Rønde, 2013), and about 10 % of the metal (Garrett et al., 2015) are currently landfilled rather than recycled.

The production and use of wind turbines have several environmental impacts. With a scarcity of critical metals, a large environmental footprint and increasing costs of steel and concrete, companies and policy-makers might favour more durable alternatives (Liu and Barlow, 2016; Liu et al., 2022). Despite this, academic literature has so far failed to apply concepts like design for reuse and recyclability (Dusch, 2013; Beauson et al., 2022) to wind turbines as part of the transition to a circular economy. Whilst the Energy Return on Investment (EROI) of wind turbines has been published and is sometimes used as an indicator of environmental performance (Davidsson, 2016), there has been little continuous progress to measure and reduce the EROI in the design of new wind turbines (Platts, 2018).

The EOL material management of wind turbines differs across technologies and regions since multiple third parties are involved in demolition or decommissioning (Ortegon et al., 2013). For instance, a construction contractor (not the wind turbine manufacturer) is usually hired and responsible for decommissioning the turbine (Veolia, 2018). Data for these activities are rarely publicly available and there are very few reports analysing the treatment of the materials after use. Cherington et al. (2012) highlight that there is little legislation present for regulating EOL waste management from the wind turbine industry in Europe. Better management and treatment of material flows before and at EOL would increase material efficiency and reduce the overall

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resource and energy demand for new wind turbines if material components were reused. Ortegon et al. (2013), Woo and Whale (2022), and Khalid et al. (2023) provide an overview of the challenges and strategies for dealing with EOL wind turbines. In addition to current repowering and decommissioning strategies, EOL alternatives such as recycling, reconditioning, reuse, and remanufacturing exist. If applied, they could help to improve the environmental and economic performance of wind turbines.

Several wind turbine manufacturers have commissioned life cycle assessments (LCAs) to assess the environmental performance and impact of their turbines. However, these assessments have three major weaknesses. Firstly, statements regarding the material flow at EOL refer to the theoretical recyclability of the material, e.g. 'recyclability [is] 81 to 85 % of turbine mass' (Garrett and Rønde, 2013). This theoretical value is rarely transformed into practice; the reports indicate that only the metals are recycled, and most of the material is landfilled (Garrett et al., 2011; Ortegon et al., 2013). Secondly, the energy requirements for recycling, material degradation, and components such as the concrete foundation are sometimes omitted. Thirdly, the system boundaries differ; in some analyses, both the cable and grid connection are included (e.g., Eymann et al. (2015)), whereas others analyse the environmental effect of the turbine only (Jensen and Skelton, 2018; Liu et al., 2019; Heng et al., 2021; Sommer et al., 2022).

The opportunity presented by the circularity of technologies lie in mitigating the environmental impact of production and end-of-life material flow management. To facilitate the transition toward a more circular economy, there is a need for performance indicators that can effectively measure progress in this domain (Haupt et al., 2017). There are several indicators for resource and environmental policy used in governmental benchmarking, but no specific ones for wind turbine material flow yet. Recent analyses have assessed the overall material flows of wind turbine systems in Germany (Volk et al., 2021), the UK (Tota-Maharaj and McMahon, 2021), and Ireland (Nagle et al., 2020). However, the focus is mainly on specific components. For example, some models provide estimates for the material demand and blade waste production of wind turbines in 2030 and 2050 (Liu and Barlow, 2017; Cooperman et al., 2021; Heng et al., 2021; Volk et al., 2021). Volk et al. (2021) provide a detailed quantification of the regional rotor blade waste in Germany until 2040, which is estimated to be in the order of magnitude of several hundred thousand tonnes (cumulative).

Different metrics are available to track progress towards a circular economy with advantages and disadvantages as analysed in a review by Corona et al. (2019). The Circularity Index (CI) proposed by Cullen (2017) is one metric that includes the energy aspects of recycling. In contrast to the Material Circularity Index proposed by the MacArthur Foundation and the EROI, the CI combines material and energy aspects in a single metric. Hence, it can more comprehensively evaluate the circularity of a system, recognising the value of maintaining materials in a useable form to avoid virgin material use, whilst acknowledging the energy input that is required to achieve this. CI has been estimated for large-scale industrial systems (Cullen, 2017), but not yet for specific technologies like wind turbines. Siemens Gamesa announced a plan to produce circular wind turbines (Siemens Gamesa, 2022), though their concept and metrics for circularity have not yet been published. Assessing wind turbine circularity requires appropriate indicators and visualisations to measure and compare different models and identify opportunities for resource efficiency improvements. The recently published DIN SPEC (DIN, 2020) on dismantling strategies for wind turbines contains guidelines for dismantling and recycling components but does not (yet) consider visualisations of current or future material flows of wind turbines. A visualisation of the material flows and discussion of interventions could enable monitoring and comparison of different resource management strategies for the circularity similar to previous material flow analyses for glass (Westbroek et al., 2021) or tungsten (Leal-Ayala et al., 2015). These analyses highlight different interventions that could improve efficiencies in the systems of material

production and use.

This paper aims to understand the material flows of onshore wind turbines, current and best practice EOL management, and wind turbine circularity to provide a better basis for decision-making. The CI is used to evaluate the circularity of the wind turbines for developing strategies for increasing resource efficiency at EOL using wind turbines in Germany as an example. The paper will address the following questions:

- 1) How can current and prospective EOL material flows of wind turbines be evaluated to inform strategy development and EOL material flow management?
- 2) What are the CIs of the three different onshore wind turbines?
- 3) Could a technology-specific CI be used as a benchmark for the transition towards the circularity of wind turbines?

2. Methodology

To assess the potential and limitations of the circularity of onshore wind turbines, data was collected to conduct an MFA. The MFA is then used to estimate the CI of material usage in onshore wind turbines and map material and embodied energy flows.

2.1. Material flow data collection

For the material flow analysis, the most frequently installed wind turbine was chosen: a 2 MW wind turbine (BWE, 2017; Deutsche WindGuard, 2016; Guezuraga et al., 2012). The analysis compares three 2 MW wind turbines from different manufacturers. The data on the material flows of the three turbines come from peer-reviewed articles and LCA reports. The selected 2 MW turbines are an Enercon E-82 (Eymann et al., 2015; Zimmermann et al., 2013), a Gamesa G8X, (Martínez et al., 2009), and a Vestas V90 (Eymann et al., 2015; Garrett et al., 2011; Garrett and Rønde, 2013).

There are different approaches for conducting an MFA and they differ in level of detail (Brunner and Rechberger, 2017; Villalba et al., 2018). To analyse circularity, a macro-level approach covering the country-wide material flows of all wind turbines could be used. This approach has been chosen for assessing the current and future material flows of large-scale wind turbine deployment in Germany (Zimmermann et al., 2013). However, for wind turbines, a micro-level approach investigating the material use and EOL strategies of selected turbines is expected to give more detailed insights into the technology-level circularity. Therefore, an assessment of typical wind turbines is chosen to illustrate the concept and visualise the flows.

A systematic life cycle assessment by (Garrett et al., 2011) reveals the average EOL practice of wind turbines from the manufacturer Vestas. Their published information is averaged and rounded but gives an overview of the current practice at Vestas. Table S-1 in the supporting material presents the underlying assumptions of quotas of recycling, landfilling, and incineration used for the visualisation of current and best practices in Germany based on the literature review. These are then used for visualising the material flows at EOL.

A database for assessing the material flows was created based on a review of publications including peer-reviewed articles, governmental reports and technical reports from wind turbine manufacturers. All peer-reviewed articles identified in the initial review were searched for relevant information on the material composition and EOL flows of wind turbines. The data obtained were of different qualities. Whereas two LCAs provided an extensive overview of the materials used for specific parts of the wind turbine (such as stainless steel, cast iron, etc.), others used aggregated categories (such as steel) for materials. The following Table 1 summarises the main phases of data collection and analysis.

The wind turbine dataset obtained from the literature review is used to map the material flows. The Sankey diagrams for the wind turbines are created by using floWeaver (Lupton and Allwood, 2017). The maps of the material flow for the three wind turbines include the following

Table 1
Phases of data collection and analysis.

Phase	Source	Description of Steps
First Data Collection	Peer-reviewed articles Governmental reports Technical reports	Collect information on material components of three different 2 MW wind turbines and store it in a database.
Data Structuring	New database with material flow information and categories	Review data from peer-reviewed journals and reviewed reports using ISO 14,044. Include wind turbine data from different manufacturers to reduce data bias. Compare different studies of similar 2 MW wind turbine models for cross-validation.
Second Data Collection	Material information from Ansys Granta EduPack (Granta, 2017; Ansys, 2022), formerly known as Granta CES EduPack.	Add new entries to the database for current and best-practice EOL management based on the available literature.
Dataset Summary	Modelled dataset	Format and structure information in dataset formatted and structured so that it could be used for the MFA.

four stages: (1) Type of material, (2) Object in turbine, (3) EOL option (current), and (4) EOL option (Best). The material flow mappings compare the current and best practices and thus enable the identification of potential waste management improvements. Following the visualisation, different strategies for improving resource efficiency can be developed. The same current and best practice EOL values are applied to the different turbines since turbine-specific information is not available and is not the focus of the analysis. The Sankey diagram of the wind turbine material flows can be used to identify opportunities to improve the circularity of the wind turbines in two ways. Firstly, material efficiency can be optimised, mainly by reducing material demand. Secondly, embodied energy flows can be minimised through increased reuse and recovery, which both reduce the energy demand relative to primary production of the material. This approach for improving circularity by using the CI is explained in more detail in the next section.

2.2. Circularity index (CI)

The technology-level CI for wind turbines is calculated to estimate the overall material circularity of the wind power system. The Circularity Index used for this analysis is defined by the following formula (Cullen, 2017):

$$CI = \alpha * \beta \quad (1)$$

where the parameter α describes the combined effects of material stock dynamics and dissipative losses, and the parameter β quantifies the energy needed for material recovery relative to the energy required for primary material production from virgin ore. The CI for steel, aluminium, cement, and plastics are taken from Cullen (2017).

2.2.1. Data for the circularity index

The CI must be estimated for the remaining materials, including copper and neodymium, for which global recovery rates are available (European Copper Institute, 2018; Rademaker et al., 2013). Table 2 summarises the steps for calculating the CI. The steps include data collection, component-wise calculation of $\alpha_{Material}$ and $\beta_{Material}$ and then

Table 2
Steps for calculating the weighted circularity index.

Step	Description
1. Collection of information in the database	Collect data on energy demand for recycling embodied energy as well as current recycling quotas and other indicators.
2. Calculation for material components	Follow calculations for obtaining $\alpha_{Material}$ and $\beta_{Material}$ from Cullen (2017).
3. CI for all n components	Collect values α and β for the different materials based on the MFA and the dataset, and use them for calculating CI_n for all n components.
4. CI of technology	Calculate CI_n values with relative mass and relative embodied energy to obtain the CI_m and CI_e .

the CI for each material. After that, the relative mass and the relative embodied energy of the material will be used as the basis for the calculation of the weighted CI.

Since the CI is only available for material flows at the level of industrial systems, but not yet for technologies consisting of different materials, the weighted arithmetic mean over all components is calculated. It is assumed that the overall circularity of technology will be equal to the sum of its n components. There are different possibilities for summing up the CI values of the components. In this analysis, the mass, as well as the embodied energy of the material flows, will be used as a weighting factor.

The relative contribution of material components and their CI to the overall CI of the wind turbine are calculated according to the following formulas: m_i : relative mass of the components as part of the overall mass of the wind turbine

$$m_i = \frac{\text{mass of component}}{\text{overall mass}} = \frac{M_i}{\sum_i^n M_i} \quad (3)$$

where e_i is the relative embodied energy of a component or material i

$$e_i = \frac{\text{embodied energy of component}}{\text{overall embodied energy}} = \frac{E_i}{\sum_i^n E_i} \quad (4)$$

These values will be summed to obtain the mass-weighted and energy-weighted CI of the wind turbine.

$$CI_m = \sum_{i=1}^n (m_i * CI_i) \quad (5)$$

$$CI_e = \sum_{i=1}^n (e_i * CI_i) \quad (6)$$

Only the materials that were explicitly named in the LCA, and for which the CI value was available or obtained from the literature review, were included in the weighted CI. If the category 'other materials' was used in the LCA, the materials were excluded.

2.2.2. Limitations of the approach

The analysis presents for the first time a technology-level calculation of the CI and visualisation of the material flows using publicly available information on mass and energy flows of different 2 MW turbines. Using the values from the literature for calculating the CI for wind turbines has three limitations: the use of aggregated data, the material categories, and the amount of energy required for recycling.

The values of globally aggregated data for material recovery and demand vary strongly across sectors and regions. Using the total material demand for sub-systems such as sector-specific systems ('steel in the construction sector' or 'steel used for wind turbines') might lead to values that better reflect the circularity of material within this system. Knowing the amount of material recovered globally does not help in assessing regional or system-specific material flows. For example, the

material flows of wind turbines in Germany could be defined as a sub-system which could be assessed in further work. Then the estimated CIs would allow a more detailed assessment of the ‘circularity of flows’ within Germany. The limitations in global CI values emphasize the need for calculating CI tailored to particular technologies within specific systems. Similar challenges arise in life cycle assessments, where variations in system boundaries and geographical conditions significantly influence overall outcomes for the same technology (Munir et al., 2016).

Broad material categories for the CI (e.g., “steel”) help to analyse industrial systems of material production but limit the explanatory power of technology-specific circularity assessments. Using the categories and CI for steel in wind turbines helps produce an approximate CI of a wind turbine but makes it difficult to compare different wind turbines due to the different types of steel used. Some LCAs use cast iron instead of stainless steel, both with different energy and material recovery properties. A more detailed circularity assessment would be required for different materials and could be part of an extended material information database.

The energy required for recovering materials and the energy for primary production vary across processes, regions, and even within Europe (European Commission et al., 2013). A global average of the CI might only be valid if it accounts for these variations by weighing energy requirement values based on global production. Moreover, the energy required for producing materials strongly depends on the supply chain and production process. Databases such as Granta (2017) include different energy intensity ranges for selected materials. More detailed information about the actual energy requirements is available within the material producers’ databases and would lead to improved estimates of the CI.

2.3. Four scenarios for assessing the circularity

Four scenarios are developed to investigate research questions 1 and 3 and to illustrate the concept and potential implications for circularity. The four “What if...?” scenarios are assessed in a static environment and consist of achievable targets compared to the base case scenario. They are based on the most often discussed strategies for reducing the environmental impact of technologies. These include material demand reduction (Allwood et al., 2017), increasing recycling and reuse and of materials (Ortegon et al., 2013), increased energy efficiency, and reduced energy demand for recycling (Fischedick et al., 2014). It is important to emphasise that our results do not represent future predictions but rather present potential scenarios to improve the circularity associated with wind turbine end-of-life resource management.

The four scenarios to illustrate changes in the CI are the following:

- 1) **Increasing Material Recovery:** What if new policies incentivise more efficient material recovery from decommissioned EOL wind turbines? Therefore, the following question is analysed: how does the CI change if material recovery is improved at EOL?
- 2) **Reducing Material Demand:** What if material demand were reduced for wind turbines, e.g. through a new tower structure with supporting cables (Weston, 2017) and lightweight design (Jamieson, 2011)? These innovations in material demand reduction could potentially impact the CI. Moreover, different turbines of the same manufacturer with the same nominal capacity require different amounts of material. Regardless of their performance in electricity generation, it would be beneficial to understand the effect a reduced material demand for the components would have on the CI. Therefore, the scenario will be based on the question: How will the CI respond to a 10 % reduction in demand for all materials?
- 3) **Reducing Energy Demand for Recycling:** What if innovations in new recycling processes reduce the specific energy requirement for material recycling? This could be achieved through process efficiency increases or new routes. Here, the question will be: how does

the overall CI change if the energy required for recycling of steel is reduced by 20 %?

- 4) **Increasing Material Reuse:** What if the concrete and steel were reusable in place because of permitting changes hypothetically? For that, a $CI=1$ for those components is assumed.

This approach does not quantify the economic implications of the different scenarios which could also be analysed to analyse resource management strategies. The economics of recovery plays a significant role in decision-making and would likely shape the strategies which are considered feasible in practice. Furthermore, wider sustainability issues such as the climate impact and social implications are not considered in this analysis.

3. Results

Based on the newly obtained dataset of wind turbine material flows, the CI is calculated for each turbine and the flows are mapped using Sankey diagrams. Then, scenarios and their effect are analysed.

3.1. Estimates of the circularity index

The CI is calculated based on the steps in Section 2.2. Values for copper (European Copper Institute, 2018) and neodymium in NdFeB magnets (Granta, 2017; Rademaker et al., 2013) are calculated with data from the literature. Based on the available collection rate for NdFeB magnets, the CI is estimated to be approximately 3 %. The values in brackets are based on a global Nd recycle fraction in the current supply of 0.01 % (Granta, 2017), leading to a CI of 0.08 %. The CI value for copper is around 19.8 %, which is larger than the other CI values due to the high rates of recovered EOL material. Some materials, e.g. carbon fibres, which are reported in the category ‘other materials,’ are excluded from the CI calculation since no material-specific CI values could be obtained.

Fig. 1 summarises the weighted CI of the different wind turbines calculated using the material and energy requirements of the materials. The CI values differ between the wind turbines. The Vestas 2 MW Turbine has the highest CI at 3.9 %, followed by Gamesa (3.8 %), and Enercon (2.2 %). The order of the turbines is the same for the energy-weighted arithmetic mean, but the values are generally higher (14.7 % for Vestas, 13.7 % for Gamesa and 11.5 % for Enercon).

Overall, the results imply that reaching a CI of 100 % is far from being obtained for the selected wind turbines due to the energy required for recycling and the complexity of full material recovery and reuse.

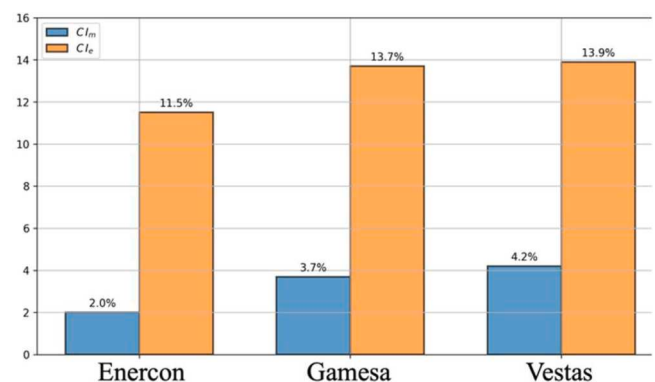


Fig. 1. Overview of the circularity indices of the three different wind turbines for the mass- and energy-weighted indices. CI_m and CI_e are the mass-weighted and energy-weighted CI, respectively.

3.2. Material flow visualisations

The Sankey diagrams present the material flows of the three wind turbines. They contrast current and best practice EOL management of the materials. Since different wind turbine manufacturers use different categories for their reporting (e.g. in LCAs), the labels in the diagrams differ. The visualisations of the material flows have several similarities and are briefly described. Although the REE flows (e.g. NdFeB flows) are rather small compared to the overall flows, they are included as a separate material flow in the diagram as they could be crucial for the further deployment of wind turbines.

3.2.1. Enercon E-82 wind turbine

For the Enercon turbine (Fig. 2), the mass flows of concrete far outweigh the other material flows. The concrete used in the foundation and the tower constitutes about 83 % of the overall material used for the turbine. The different steel components in the foundation, tower, and nacelle make up about 14 % of the material. The material flow of rotor blades is approximately 1 % of the overall turbine mass. The NdFeB magnets weigh less than 360 kg, or about 0.01 % of turbine mass, and are not visible in this diagram.

3.2.2. Gamesa G8X wind turbine

The mass flows of the Gamesa turbine of concrete outweigh the other

material flows and make up about 72.7 % of the overall material used for the turbine. The steel components contribute about 24.3 % of the material. The material flow of rotor blades is approximately 2.3 % of the overall turbine mass. The turbine including the foundation has the lowest overall mass of the three turbines. The foundation accounts for the biggest material share of landfilled material at EOL; more than 58 % of the material is being landfilled and less than 42 % is being recycled. As with the Enercon turbine, most of the concrete goes to landfill according to the LCA data available. As previously, some of the steel used in the foundation is also landfilled. Again, the entirety of the blades is currently landfilled or incinerated in waste incineration plants. However, with a relative mass of 1 %, their overall contribution to the landfilled material is rather small. If the focus is, however, on the recovery of materials or mitigation of emissions, this material flow could be significant (Fig. 3).

3.2.3. Vestas V-90 wind turbine

Fig. 4 and Fig. 5 show the material and energy flows of the Vestas wind turbine. As with the other turbines, the mass flows of concrete for the Vestas turbine outweigh the other material flows. The concrete used in the foundation and the tower represents about 72.9 % of the overall material. The different steel components in the foundation, tower, and nacelle make up about 23.8 % of the material.

Fig. 4 shows the embodied energy flows based on the material

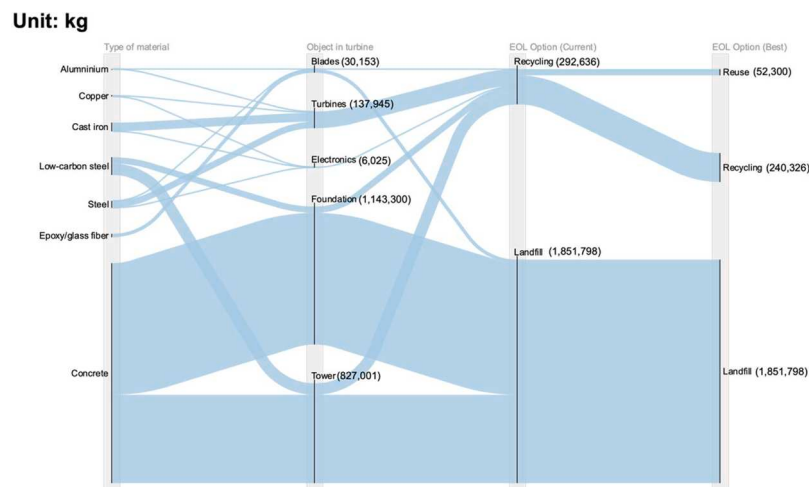


Fig. 2. Enercon E-82 2 MW Wind Turbine Material Flows [in kg]. Flows are colour-coded by the object/component in which they are used. The EOL option (current) and EOL option (best) are based on the assumptions in Table S-1 in the Supporting Information.

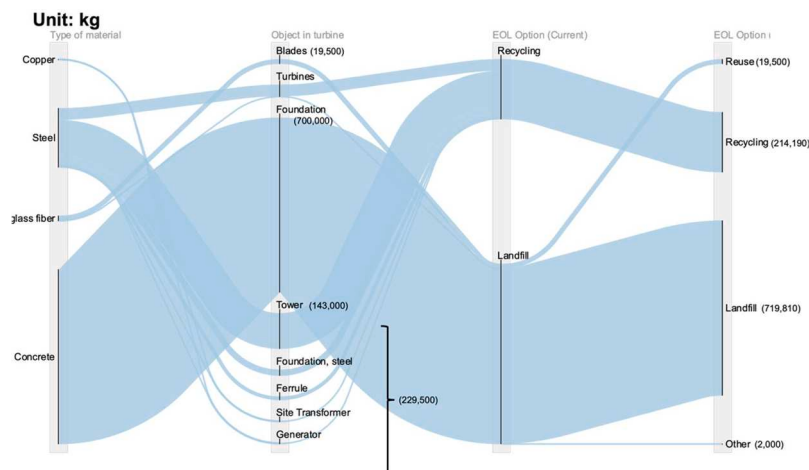


Fig. 3. Gamesa G8 x 2 MW Wind Turbine Material Flows [in kg]. The EOL option (current) and EOL option (best) are described further in the Supporting Information.

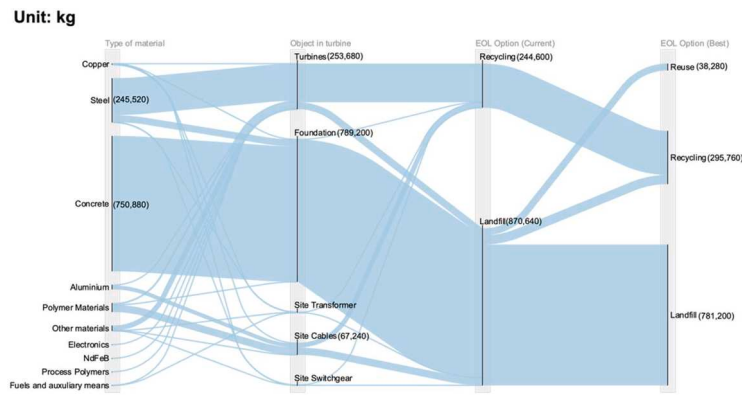


Fig. 4. Vestas V-90 – Material Flows [in kg]. The EOL option (current) and EOL option (best) are described further in the Supporting Information.

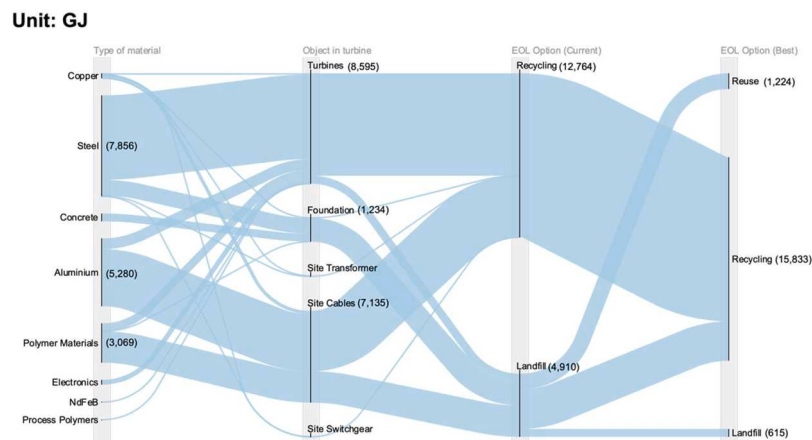


Fig. 5. Vestas V-90 – Embodied Energy Flows [in MJ]. The EOL option (current) and EOL option (best) are described further in the Supporting Information.

information in Granta (2017) in MJ. The mass flows (in kg) are multiplied by the specific embodied energy of the materials [MJ/kg]. The widths of the arrows strongly differ from the previous mass flow visualisation in Fig. 3. Now, the arrows representing steel and aluminium are much bigger than the flows of concrete. This implies that the specific embodied energy of these streams is much bigger than the specific embodied energy of cement. Although the relative mass of cement is much larger than that of the other materials, its relative embodied energy content is comparatively low. In short, it can be inferred from the

diagram that the mass and embodied energy flow strongly differ for the same wind turbine.

3.3. Impact of changes in material and energy use

The four different hypothetical scenarios increase the CI. For simplicity, the scenarios are only applied to the best-performing turbine for which LCA data is available, the Vestas 2 MW turbine. Fig. 6 visualises the impact of the different scenarios, showing the relative change

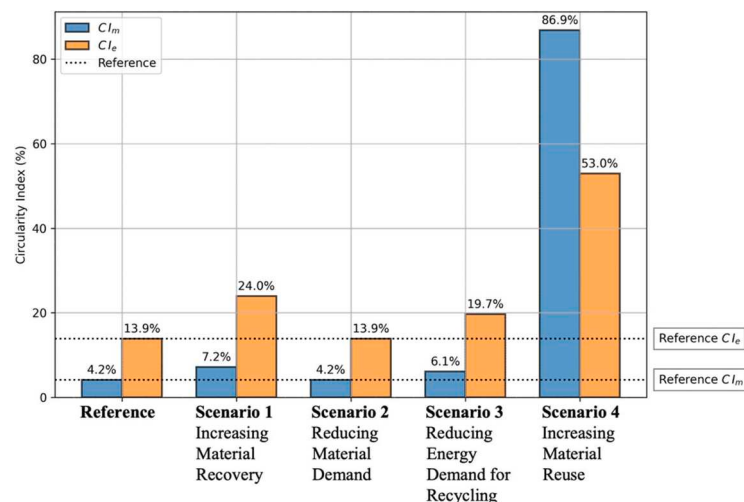


Fig. 6. Impact of different Scenarios on the Circularity Index. CI_m and CI_e are the mass-weighted and energy-weighted CI.

of the CI. For this, a one-change-each-time analysis is used.

Scenario 1: Increasing Material Recovery by 10 %: Increasing the material recovery from turbines after EOL through promoting reuse and increased recycling has a clear effect on the CI. Increasing the material recovery at EOL by 10 % (i.e., with $CI=1$) directly increases the value of α and hence the overall CI by 10%. This leads to an increase in the CI.

Scenario 2: Reducing Material Demand by 10%: Reducing the mass of the material of every component in the wind turbine by 10% leads to an interesting finding. The overall turbine mass is reduced and the relative mass of every component changes. For the analysed 2 MW wind turbine, this leads to no change in the mass- and energy-weighted CI.

Scenario 3: Reducing Energy Demand for Recycling by 20%: The theoretical β -value is increased if the relative factor of energy requirements for recycling divided by energy requirements for primary production decreases. When the efficiency of recycling processes increases, the CI value also increases. The overall effect on the mass- and energy-weighted CI is significantly large.

Scenario 4: Reusing foundation and steel material. In the hypothetical scenario with the reuse of the steel and concrete foundation, the circularity index is significantly increased up to 87 % (mass) and 53 % (energy) respectively.

The results of the analysis indicate that wind turbine circularity measured through the CI is currently low, i.e. 4 % (mass-weighted CI) and 14 % (energy-weighted CI). Different strategies could be applied to reduce the materials and energy required for the turbine and to improve the EOL resource management, thus increasing the CI. Reusing components, i.e. through material recovery or repowering has the biggest effect on the CI.

4. Discussion

Managing the EOL material flows of wind turbines in Germany will be increasingly challenging as more wind turbines will be decommissioned over the next years. A range of options for material flow management is currently being investigated. The key findings of this work are discussed about the current status and data availability, policy implications and further work.

4.1. Current status and potentials for increasing wind turbine circularity

Wind turbine material flows are currently far from circular, with the potential for diverting materials from landfills to recycling and reusing some materials. To improve this, more effective circular strategies must be pursued. These combine increased recovery at EOL, reduced material demand, and increased secondary production. The scenario analysis indicates that these strategies increase the CI. However, wind turbine designs have not historically been optimised for component reuse and effective EOL management (Ortegon et al., 2013). If this is not addressed, the overall potential to increase the CI might be limited. An especially important strategy is the reuse of components. This approach could be employed when repowering wind turbines where the reasons for decommissioning are economic, rather than technical.

The foundation accounts for the biggest material share of landfilled material; more than 61 % of the material is currently landfilled and less than 39 % is recycled. This highlights one problem with previously reported indicators; the reported '81–85 % wind turbine recyclability' used in the LCA by Garrett et al. (2011) excludes the concrete foundation and some other components. The visualisation of material flows highlights the potential for improved EOL material flow management. For example, the diagram could be used to understand that some steel components (e.g. low-carbon steel in the nacelle) can be reused with repowering rather than recycled. Although some components seem to be reusable from a material perspective, such as the concrete foundation, they are currently not reused, e.g. in a repowering scheme, since new turbines require a new planning and approval procedure. This leads to a

situation in which the full foundation is removed (and typically land-filled) and not reused for repowering (Nguyen and Rogers, 2018). However, for the CI, recycling of concrete might not be the best alternative to reuse; depending on the secondary process, the energy requirements are between 1,200 and 3,150 MJ/t, which is close to the energy requirements for primary production (3,400 MJ/t) (Worrell et al., 2008). Here, further analysis of the possible cascade uses of the foundation concrete as recycled aggregates might provide even more detailed insights into the trade-offs between energy requirements, material quality, and costs associated with the processes.

Scenario analyses highlight both the need for improved monitoring of EOL streams and the need to identify options for saving energy and mitigating energy-related emissions by prioritising material demand reduction and recycling processes. Current LCAs of wind turbines (e.g. Garrett et al., 2011) do not consider energy requirements for recycling. The visualisation of the embodied energy flows in the different material categories facilitates a greater understanding of where material efficiency increases might be most promising for reducing the energy demand for primary production and overall energy demand. For example, it is possible to (structurally) reuse or recycle some of the most energy-intensive materials, which are currently landfilled. If it is possible to do so with lower energy requirements than their primary production, this effectively increases the overall circularity of the wind turbine. These recycling processes might even lead to lower costs than the energy-intensive primary production processes.

Scenario 4 demonstrates that material demand reduction and intensive reuse of steel and concrete foundations significantly increase the circularity index. The literature on the options for material demand reduction strategies provides examples for national production systems (e.g. Song et al., 2023) as well as technologies, e.g. wind turbines (Yang et al., 2023). One example of wind turbines is the lightweight design of turbine towers (Weston, 2017). The scenarios exemplify a strong difference between the mass-weighted and energy-weighted CI. The mass-weighted CI is generally much lower. This implies that the components with large amounts of energy required for primary production have high CI values. This is due to high recovery quotas and relatively low energy requirements for secondary production compared to primary production. Hence, with increasing use of secondary materials, the CI can be reduced significantly. This dramatically increases the energy-related factor β in the CI equation.

4.2. Policy implications

The CI alone will not solve the challenge of the EOL management of wind turbine material flows, but it sheds light on the lack of circularity of systems and technologies and informs policymaking in Germany and other countries. Applying the CI and using the values for bulk materials presented by Cullen (2017) on wind turbines showed that they are currently far from the ideal of a circular economy of wind turbine material flows. Mapping the material and energy flows increases the understanding of circularity and can constitute an effective lever for implementing effective measures for a transition to a circular economy.

On a micro-level, it is possible to use the CI as a benchmark for comparing different emerging technologies. For instance, wind turbines could be compared for their circularity, recyclability, and energy requirements by developing minimum CI values and development pathways with stakeholders from industry, policymaking, and research. However, the availability of material flow information on wind turbines, especially at EOL, is quite limited, with very few wind turbine manufacturers publishing detailed LCAs or up-to-date information about current material flows and EOL management. This lack of primary data hinders the comparison of wind turbines from different manufacturers. Nonetheless, some researchers (e.g., Garrett (2017)) have agreements with wind turbine manufacturers to publish aggregated information about the recycling and recovery of components, which could help assess current and future EOL strategies. In the future, LCAs and

environmental product declarations (EPDs) could include the CI or other relevant information to increase the availability of data to inform EOL resource management strategies. For example, the draft of the European Sustainability Reporting Standard (ESRS) E-5 contains reporting requirements for circularity strategies (EFRAG, 2022).

On a macro-level, it is essential to apply the CI to other production systems and technologies to track progress towards a more circular economy. This could facilitate comparing different circularity strategies' estimated cost and efficacy. The CI adds a new dimension to sustainability assessments, considering both material flows and energy requirements for material production and recycling. Currently, governmental reports (e.g. Umweltbundesamt, 2017) focus on recycling and recovery quotas of consumer goods and general construction waste. There remains a gap in reporting on recycling that takes account of both material flows and energy requirements for material production and recycling. It is crucial to avoid misleading decisions targeted at resource efficiency by only using one of the weighted CIs. For instance, material demand reduction strategies might not be accurately reflected in the CI, but could still reduce the overall environmental impact (Song et al., 2023). Nonetheless, the CI could play a vital role in monitoring progress towards circularity and encouraging increased resource efficiency and recycling.

4.3. Future work

Several areas require further work for reducing material demand and increasing lifetime, conducting economic analysis, and assessing best practices at EOL. For instance, exploring strategies that extend the useful lifetime of wind turbine foundations and reduce long-term energy and material demand could be beneficial. Non-destructive testing of existing concrete foundations to ensure quality, accompanied by reforms to the design, planning, and approval of new turbines, may facilitate more frequent reuse of the existing stock of foundations as well as other components. Moreover, trade-offs between the short-term impact of over-specifying foundations and the long-term potential to support higher-capacity turbines in the future could be explored for new designs.

While this paper does not cover the financial and carbon impacts of different EOL options (including reused concrete components to avoid new production.), it could be included in future work if more industrial information were available. "Sunk economic value" could be included in the material flow mapping in this case, and strategies that emerge from the analysis could be tested with key stakeholders, such as turbine designers, decommissioning firms, and policymakers to understand the barriers to implementation and to what extent they can be mitigated.

It might be worthwhile to conduct further studies that evaluate CIs on a national or local level for all components of wind turbines to expand this analysis. Wind turbine manufacturers or their associations could provide the CI for materials, based on recently demolished or decommissioned EOL material flows on a country-level. Using the global averages and recovery quotas may underestimate the best practice of wind turbine manufacturing. If some companies have higher material recovery quotas at EOL, it is currently not represented in the presented CI estimates, since the information about average EOL management of the components has been based on the few publicly available reports.

Future analysis of the circularity of specific technologies for each component (metals, reinforcements, polymer matrix, concrete) could include an extended analysis of the uncertainty in the data and variances of material recovery and reuse quotas by including different manufacturers and the locations of the turbines. However, this can only be achieved if the information on the EOL treatment of material flows is regularly reported and made publicly available by wind turbine manufacturers. Similarly, further best practice scenarios could assess the impact of the use of low-carbon materials, e.g., from material recycling, which could have a significant impact on overall emissions and reduce the environmental impact from the production of materials used for the foundation and turbines.

5. Conclusions

The transition towards a circular economy requires changes to the current system of material use to conserve resources, reduce energy consumption, and increase the circularity of material flows. Today, little is known publicly about actual recycling rates at the end-of-life and the energy requirements for recycling and material reuse are usually not published. The assumptions about the 'recyclability' used in LCAs are poorly monitored and ignore the energy requirements, whilst some components (such as the concrete foundation) are not included in the scope of the analyses. This study discusses the challenges and potential of achieving material circularity in wind turbines in Germany. It highlights the opportunities for increasing transparency in actual recycling rates and the need for better resource management policies.

The Circular Indicator (CI) is proposed as a benchmark to improve circularity and is discussed as a more realistic representation of the potential for circularity as it captures material aspects of circularity as well as the energy requirements associated with restoring EOL materials to a useful state. This study outlines a methodology for calculating the CI for wind turbines and explores different strategies for improving CI performance. The analysis highlights the importance of recycling and material demand reduction through component reuse, which is currently not optimized in EOL practices and wind turbine designs. Finally, this study calls for better access to current EOL practices and more accurate materials flows data and engagement with key stakeholders to improve the feasibility of the proposed strategies.

CRedit authorship contribution statement

Lukas Gast: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Fanran Meng:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Dai Morgan:** Conceptualization, Writing – review & editing.

Declaration of competing interest

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.

Data availability

I have shared all data in the supporting information.

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Supplementary materials

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