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Quantifying circular economy pathways of decommissioned onshore wind turbines: The case of Denmark and Germany

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A R T I C L E I N F O

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A B S T R A C T

Onshore wind turbines in Europe are increasingly reaching the end of their first lifecycle. Their pathways after decommissioning call for the establishment of circular supply chains (e.g. refurbishment or recycling facilities). Reliable component and material flow forecasts are particularly crucial for the development of blade-recycling capacity, as such facilities still need to be established. However, current forecasts assume a static decommissioning time and neglect a second lifecycle for the wind turbines and their blades, which has resulted in potential recycling quantities being over-estimated. This study overcomes these issues by (i) collecting empirical data on the circular economy pathways taken by decommissioned onshore wind turbines in the mature onshore wind markets of Denmark and Germany, and by (ii) proposing a new component and material flow forecasting model for the more reliable planning of blade-recycling capacity. The results reveal that ~50–60 % of decommissioned onshore wind turbines in Denmark and Germany were exported mainly to other European countries. If the second lifecycle practices of the past are continued in the future, annual blade masses for domestic recycling are expected to range between ~380–770 tonnes for Denmark and ~4400–11,300 tonnes for Germany in the next ten years. This study finds that the threshold values of blade volumes for an economically viable blade-recycling facility can be reached in Germany with its large operating wind-turbine fleet, but the recycling of Danish wind turbine blades would have to rely on aggregating resource flows from other countries or industries. By modelling the cascading order of a sustainable circular economy and the EU Waste Hierarchy Directive, this study improves the decision-making basis for policy makers and companies to achieve sustainable resource use along the wind industry's entire value chain.

1. Introduction

The notion of a circular economy is contributing to several Sustainable Development Goals (SDGs), among others to SDG 12, the responsible consumption and production of resources (Schröder et al., 2019; European Commission, 2020; Velenturf and Purnell, 2021, p. 1444). By decoupling from virgin materials and limiting waste to a minimum, a circular economy can reduce material footprints, material consumption (SDG 12.2) and waste generation (SDG 12.5) (Schröder et al., 2019, p. 89). Despite the potential, the global circular material use rate was still marginal at 7.2 % in 2023 (Fraser et al., 2024). The EU had a higher share of recycled materials of overall material use at 11.5 % in 2022, but current progress is not in line with the target of 23.4 % by 2030 (Eurostat, 2024). In addition to improving the circularity rate, there are further indicators to consider (e.g. private investments, gross value added, consumption footprint), whose overall performance varies across European countries (Moraga et al., 2019; D'Adamo et al., 2024; Eurostat, 2024). Moreover, actions to promote a circular design of products and production processes are required, which currently lack comprehensive indicators (European Court of Auditors, 2023).

A transition to a circular economy is also important for EU's wind-energy markets: The immense expansion targets for installed capacity, which are crucial to the EU's goal of a transition to climate neutrality by 2050, require significant amounts of resources sourced from just a few countries (Carrara et al., 2020; Rystad Energy, 2023). Moreover, the

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Nomenclature

Δt	Time spread from 10 % to 90 % decommissioning of the blade mass
λ	Scale parameter of Weibull function
exp	Exponential
$F(t)$	Weibull function
f_{reuse}	Fraction of exported blades
k	Shape parameter of Weibull function
m_0	Initial blade mass installed at t = 0
m_{decom}	Potential blade mass for decommissioning
$m_{recycle}$	Potential blade mass for recycling in a country
t	Time after the initial year of installation
$t_{½}$	Time at which half of the installed blade mass has been decommissioned

material extraction and processing accounts for approximately 70–80 % of the already shallow environmental footprint of wind turbines (Bonou et al., 2016; United Nations Economic Commission for Europe, 2021). In this light, the transition to a circular economy has recently gained attention in the EU's wind-energy markets from research, policy and industry, as it is meant to improve the environmental performance of wind-energy supply chains and decrease dependence on sourcing virgin materials from single countries (European Commission, 2020, 2023a). Moreover, a circular economy is seen to address concerns regarding the handling of upcoming waste volumes from the installed wind-turbine fleet (WindEurope, 2020; Graulich et al., 2021, pp. 45–50; Wang et al., 2022, pp. 12–13). The EU, particularly Denmark and Germany, have historically been pioneers in the development of wind-energy technology and the installation of wind turbines (Schaffarczyk, 2023, p. 49; Zhao, 2023). As a result, wind turbines are increasingly being decommissioned in European countries or have already been decommissioned (WindEurope, 2020; Zhao, 2023). Possible pathways after decommissioning are, in cascading order, direct reuse, refurbishment, remanufacturing, repurposing, recycling, incineration with or without energy recovery, and landfill with or without remining (Velenturf, 2021; Kramer and Beauson, 2023). From the perspective of a sustainable circular economy (Velenturf and Purnell, 2021) and the EU Waste Framework Directive (European Commission, 2008), turbine and component reuse is preferred in principle ahead of material recycling and energy recovery. Waste creation and long-term landfilling should be eliminated, as called for by the European wind industry for turbine blades (WindEurope, 2020). As such, retaining structural value through lifetime extension and multiple lifecycles while simultaneously establishing sustainable recycling solutions is crucial for more sustainable resource flows (Bocken et al., 2016).

Investments in circular supply chains (e.g. refurbishment or recycling facilities) depend on reliable component and material flow forecasts (Kramer and Beauson, 2023; Potočnik and Teixeira, 2023; Fraser et al., 2024, p. 24). For instance, a new blade glass-fibre recycling plant in Denmark requires ~10,000–15,000 tonnes annually to be economically viable (Villadsen, 2023). However, forecasts vary widely and generally differ from the actual flows within the wind market (summarised in Section 2.2). This suggests that, instead of decommissioning and recycling after reaching the design lifetime of 20 years, alternative pathways are being taken up for wind turbines at the end of their first use phase (International Electrotechnical Commission, 2019; Graulich et al., 2021, p. 52). Hence, understanding pathways after decommissioning is essential, particularly for wind turbine blades that are still devoid of sustainable and commercially viable recycling routes (Graulich et al., 2021, pp. 48–49; Beauson et al., 2022; Rentizelas et al., 2022). However, research has so far not clarified which pathways were chosen for decommissioned onshore wind turbines, whether reusing wind turbines and blades is common practice in Europe (Graulich et al., 2021, p. 52; Kramer and Beauson, 2023), nor how this may affect domestic waste volumes. This will first affect the most mature onshore wind markets in Europe, Germany and Denmark, which indeed have the longest and largest histories in onshore wind decommissioning (Zhao, 2023). Other countries will likely follow practices from these early movers. This paper will hence answer research questions RQ1: "*Which pathways were chosen for the decommissioned onshore wind turbines and their blades after their first use phase in Denmark and Germany?*" and RQ2: "*How do the chosen pathways affect the expected component and material flows of the installed onshore wind turbines in Denmark and Germany when planning blade recycling capacity?*". Therefore, the research objectives are as follows:

- Identify whether a second lifecycle of wind turbines and their blades has been common.
- Provide a more reliable forecasting method for planning domestic blade-recycling capacity.
- Forecast the expected annual blade masses of installed onshore wind turbines in Denmark and Germany and assess the likelihood that threshold values for establishing economically viable blade-recycling facilities will be met within the next ten years.

To answer the research questions, the paper is structured into six sections, starting with a literature review on circular economy strategies (Section 2.1) and component and material flow forecasts for wind turbines (Section 2.2). Firstly, theoretically possible circular economy pathways that decommissioned wind turbines and their blades could follow are identified. Secondly, the approaches chosen by existing component and material flow models for forecasting blade masses for recycling are determined and research gaps identified. Section 3 describes the methodology which is linked to the theoretical understanding and aims at closing the identified research gaps by answering RQ1 and RQ2. First, market data are selected (Section 3.1), followed by description of a method of determining the chosen pathways of decommissioned onshore wind turbines (Section 3.2). Semi-structured interviews with 16 experts are conducted to quantify the circular economy pathways of decommissioned onshore wind turbines in Denmark and Germany. Hence, to be able to answer RQ1, the decommissioning history of more than 20 years is reviewed with the interviewed experts, who cover more than 50 % of each respective market. The retrospective data collection may lead to uncertainties, but no data have been collected to date. Finally, Section 3.3 introduces a new component and material flow method for planning blade recycling in Denmark and Germany. The forecasts of the proposed models are based on historical data that cannot necessarily be extrapolated into the future. However, it reflects the most recently available market data and integrates the newly collected data on the followed pathways, which enables RQ2 to be answered. The results are presented in Section 4, discussed in Section 5 and conclusions are summarised in Section 6.

2. Literature review

This section first reviews the literature on circular economy strategies and the resulting pathways that rotor blades could take after wind turbines are decommissioned (Section 2.1). Thereafter, the state of the art on component and material flow models for wind turbines and their blades is presented (Section 2.2).

2.1. Circular economy strategies

The EU (European Parliament, 2023) describes a circular economy as "*a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. In practice, it implies reducing waste to a minimum. When a product reaches the* *end of its life, its materials are kept within the economy wherever possible thanks to recycling.*" Accordingly, circular strategies, also called R-principles, are applied in a cascading order to narrow, slow and close resource flows (Bocken et al., 2016, p. 309). These strategies are organised in an "R-ladder", with the highest priority placed on the top (Potting et al., 2017, p. 15). Those potentially applied after a first lifecycle of a wind turbine are the strategies related to slowing and closing resource flows defined as R3-R9, while R0 Refuse, R1 Rethink and R2 Reduce do not fall within the scope of this paper (Potting et al., 2017; Velenturf, 2021; Kramer and Beauson, 2023):

- R3 Reuse: Direct reuse of products for the same function (European Commission, 2008, p. 5). This might include inspecting, cleaning and repairing parts to enable reuse (Defra, 2011, p. 3), but it does not foresee overall refurbishment or remanufacturing.
- R4 Repair: Extend lifetime of products (Reike et al., 2018, p. 255) by restoring them after decay or damage to a usable state (Bocken et al., 2016, p. 311).
- R5 Refurbish: A multi-component product is updated by replacing or repairing some components (Potting et al., 2017, p. 15; Reike et al., 2018, pp. 255–256).
- R6 Remanufacture: Through a fully documented standard industrial process, the product's function is brought up to at least the originally manufactured quality (International Resource Panel, 2018, p. 46). This includes disassembly, checking, cleaning and, if required, replacing or repairing parts and providing a product warranty (Reike et al., 2018, p. 256; Deutsches Institut für Normung, 2023, pp. 7–8).
- R7 Repurpose: Structural reuse of products or components, but for a different function (Velenturf, 2021, p. 16).
- R8 Recycle: Reprocessing waste "into products, materials or substances whether for the original or other purposes" (European Commission, 2008, p. 5).
- R9 Recover: "energy recovery and the reprocessing into materials that are to be used as fuels or other means to generate energy" (European Commission, 2008, p. 5).

This paper suggests defining wind-turbine lifecycle pathways depending on the R-ladder chosen in the second lifecycle that either the full turbine or the components are undergoing, as illustrated for turbine blades in Fig. 1. In principle, circularity increases when R-principles are used further up the ladder and the overall lifetime is maximised. That said, over the operational life of a wind turbine or components, several R-principles can be applied in multiple lifecycles, leading to several possible pathways. Three examples for blades, two circular paths and one linear, are illustrated in Fig. 1.

The "Linear path" is considered a fully linear path as after the first lifecycle, the wind turbine blades are landfilled. In the "R5-Circular path" and "R3-Circular path", the blades or the entire turbine enter a second lifecycle. In the "R5-Circular path" the blades are refurbished (R5) and have a second lifecycle as spare parts. After the second lifecycle, the energy is recovered (R9) through cement co-processing (Beauson et al., 2022). The "R3-Circular path" is the most circular of these examples. It foresees direct reuse (R3) of the turbine at a different site, followed by repair (R4) for use as spare parts, and material recycling (R8) after the last lifecycle.

R3-R7 have in common that they aim to retain the structural value, i.e. to enable a second lifecycle or, more generally, further lifecycles of the decommissioned wind turbine and its blades. R3-R6 strive for structural reuse with the same function, in contrast to R7, which provides for structural reuse with a different function. Research on second lifecycle practices (R3-R7) for wind turbine blades is rare and focuses mostly on repurposing (R7) (Kramer and Beauson, 2023). Accordingly, several authors have called for more research on second lifecycle practices to understand their potential. For example, Kramer and Beauson (2023) note a lack of research on second lifecycle practices of wind turbines blades and Ortegon et al. (2013) highlight the need to further assess the barriers and enablers for remanufactured wind turbines. Moreover, Andersen et al. (2016), Pehlken et al. (2017), Kramer and Schmidt (2022) and Kühne et al. (2022) emphasise that the development of the second-hand market for turbines and components requires further investigation to understand the potential impact on the estimation of component and material flows for recycling.

If structural reuse becomes impossible during the lifetime of a blade, then resource flows should preferably be closed through material recycling (R8) or, alternatively, energy recovery (R9). Recycling (R8) is increasingly being researched to develop an alternative to energy recovery (R9) and landfilling blades. However, a high-value and economically scalable recycling process for composites still needs to be developed (Kramer and Beauson, 2023). So far, cement co-processing (R9) is an economically scalable process that has, in comparison to landfill, a positive environmental footprint when replacing fossil-based energy in cement manufacturing (Nagle et al., 2020; Beauson et al., 2022). The landfilling of blades will likely not be possible from 2025 onwards, as the industry has called for a ban on landfills in the EU

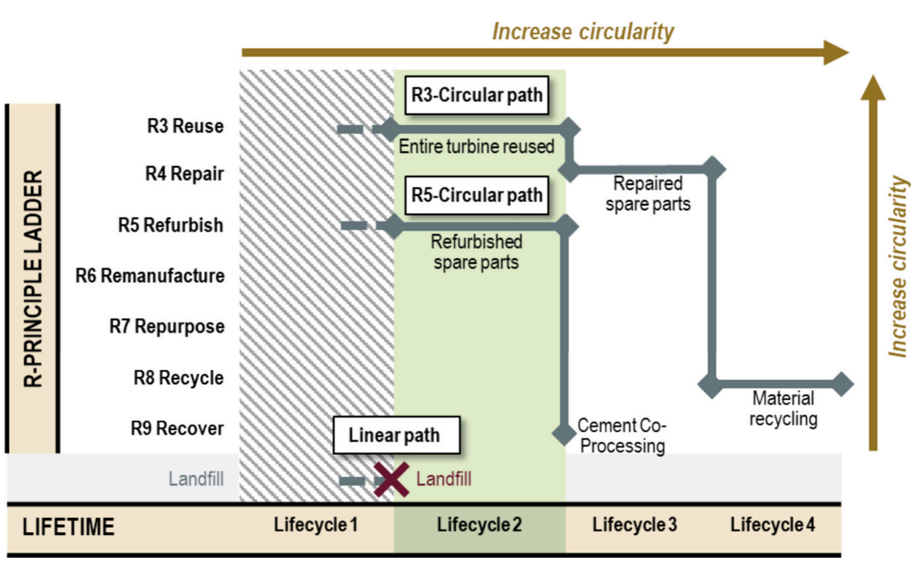

Fig. 1. Possible pathways of wind turbine blades after decommissioning an onshore wind turbine and highlighting three examples of a wind turbine blade's life. Inspired by Kramer and Beauson (2023); Potting et al. (2017); Velenturf (2021).

(WindEurope, 2020). This underlines the need for progressing with the development of higher circular economy strategies for handling decommissioned wind turbines, and in particular their blades.

Research has not yet analysed which pathways are currently the most common anywhere in the world. Statistics for the EU are lacking (Graulich et al., 2021, p. 52). Hence, this paper investigates which pathways were taken for the decommissioned onshore wind turbines and their blades after their initial use phase in Denmark and Germany (see RQ1). The study explores whether a second lifecycle as a blade (R3-R6) was taking place. In distinction to these second lifecycle pathways, R7-R9 are seen as strategies that do not keep the structural value with the same function. Hereafter they are therefore referred to as "other waste-handling pathways".

2.2. Component and material flow forecasts of onshore wind turbines for planning blade-recycling capacity

Developing supply chains for circular economy strategies requires reliable component and material flow forecasts. The scope of this study is to investigate how expected component and material flows for planning blade-recycling capacity are affected by a blade's second lifecycle, whether reusing the entire turbine or reusing it as a spare part (see RQ2). Hence, the required information is (i) which turbines were installed when and where, (ii) when they are expected to be decommissioned and (iii) whether they have a second lifecycle. Seventeen publications are identified, including one study dedicated to Denmark (Abrahamsen et al., 2023) and four covering Germany (Pehlken et al., 2017; Zotz et al., 2019; Volk et al., 2021; Kühne et al., 2022). Studies focusing on offshore turbines only are excluded. All papers focus on expected quantities of other waste-handling pathways, one addressing repurposing (Delaney et al., 2021) and the remainder end-of-life quantities (e.g. Kühne et al., 2022; Andersen et al., 2016). Although the publications address different countries, they have in common that most of them base their predictions on the blade mass of installed turbines in their respective markets, i.e. excluding planned installations in their predictions (e.g. Abrahamsen et al., 2023; Chen et al., 2021). Moreover, their forecasts are expressed in blade mass (tonnes), which is calculated with approximations based on installed capacity (e.g. Lefeuvre et al., 2019) or a regression function based on the rotor diameter (e.g. Abrahamsen et al., 2023; Volk et al., 2021).

The majority of papers assume that decommissioning dates are static, mostly with an expected service life of 20 years being equal to the design lifetime of turbines, hereafter referred to as a "20-year scenario" (International Electrotechnical Commission, 2019; Volk et al., 2021). In six papers, a distribution function is applied that is either calculated by approximation (Delaney et al., 2021), with reference to the historical distribution of decommissioned turbines (Lichtenegger et al., 2020) or as a function based on the historical ratios between decommissioned and installed turbines per installation year (Abrahamsen et al., 2023). The latter method has been applied to the Danish wind-turbine fleet (Abrahamsen et al., 2023) but not yet to Germany; Pehlken et al. (2017), Zotz et al. (2019), Volk et al. (2021) and Kühne et al. (2022) assume a static decommissioning time of 20 years. With respect to the possibility of a second lifecycle, 12 papers do not consider any further lifecycle for wind turbines or their components (Volk et al., 2021; Kühne et al., 2022). Two of the 17 papers forecast decommissioning and not end-of-life quantities (Delaney et al., 2021; Abrahamsen et al., 2023), therefore not making any assumptions about a second lifecycle. Three papers use second lifecycle scenarios by applying a simple assumption (Andersen et al., 2016; Pehlken et al., 2017; Tota-Maharaj and McMahon, 2021). The simple assumptions vary from a reuse fraction of 10 % (Tota-Maharaj and McMahon, 2021) to 50 % for all onshore turbines (Andersen et al., 2016) to differentiating between small, medium and large-scale turbines. For instance, authors assume that 54 % (Pehlken et al., 2017) or 100 % (Andersen et al., 2016) of turbines below 1 MW are reused. For papers focusing on Denmark or Germany, only the study by Pehlken et al. (2017) considers a second lifecycle. For turbines below 1 MW in Germany, they assume that 60 % will be decommissioned already after 15 years, of which 90 % are then exported for reuse.

To conclude, different assumptions for the time of decommissioning and whether a second lifecycle takes place, do exist in the literature. The research gap we have identified is twofold and is addressed by this study. First, the potential transferability of the introduced method for determining the time of decommissioning by Abrahamsen et al. (2023) has not yet been carried out. Secondly, methods that systematically integrate second lifecycle practices are currently missing. To integrate second lifecycle practices in component and material flow forecasts, the collection of historical data is first required. Hence, as such data do not yet exist, this study attempts to determine the fraction of decommissioned onshore wind turbines in Denmark and Germany that have entered a second lifecycle. Based on the collected information, second lifecycle considerations can be integrated into the forecasting of components and material flows of the installed blade mass for planning blade-recycling capacity.

3. Methods

The research methodology is summarised in Fig. 2 and has the aim of closing the identified research gaps in the light of forecasting the blade mass of recycling installed wind turbines in a particular country (see Section 2.2). The methodology is applied to the installed onshore wind turbines in Denmark and Germany and consists of three parts of which the first two parts function as inputs for the third part.

First, market data representing the installed Danish and German onshore wind turbines are selected, assessed and prepared. As shown in Fig. 2, these data enable the calculation of the installed blade mass of the respective markets (Section 3.1). Second, a method to determine the chosen pathways of decommissioned onshore wind turbines is developed (Section 3.2). The data on circular economy pathways for the respective markets is collected using the qualitative method of expert interviews, as no empirical data exist. Third, a new component and material flow method for planning blade-recycling capacity for Denmark and Germany is established, which integrates the state of the art on defining the decommissioning time and integrates the collected empirical data on secondary lifecycle practices (Section 3.3). The models are compared with existing component material flow models and to economically viable threshold values identified for establishing a recycling facility. Each step in the research methodology is further described in the subsequent sections.

3.1. Market data for onshore wind turbines in Denmark and Germany

The datasets chosen to represent decommissioned and operating onshore wind turbines are as follows: for the Danish market, the master data register of wind turbines of the Danish Energy Agency (DEA) (Danish Energy Agency, 2022) (data extracted 31/01/2022); and for the German market, the market master data register (MaStR) of the Federal Network Agency (Bundesnetzagentur, 2023), supplemented by the annual decommissioned capacity according to Deutsche WindGuard (Deutsche WindGuard, 2023; data extracted 30/06/2023) and on behalf of the Federal Ministry of Economics and Climate Protection (BMWK) (Lüers et al., 2023; data as of 31/03/2023). The selected data are publicly available and free to use, which promotes the repeatability of the methodology. The suitability of the selected data is assessed through cross-checking with other databases and studies (Volk et al., 2021; Kühne et al., 2022; Abrahamsen et al., 2023; Deutsche WindGuard, 2023; Zhao, 2023, further detailed in the Supplementary information S1), leading to the following conclusions. Firstly, the operational and decommissioning data representing Denmark's wind turbines are derived from the Danish market register. For Germany, secondly, multiple sources are used, as the market register (MaStR) does not provide full decommissioning data, particularly prior to 2019 (Deutsche

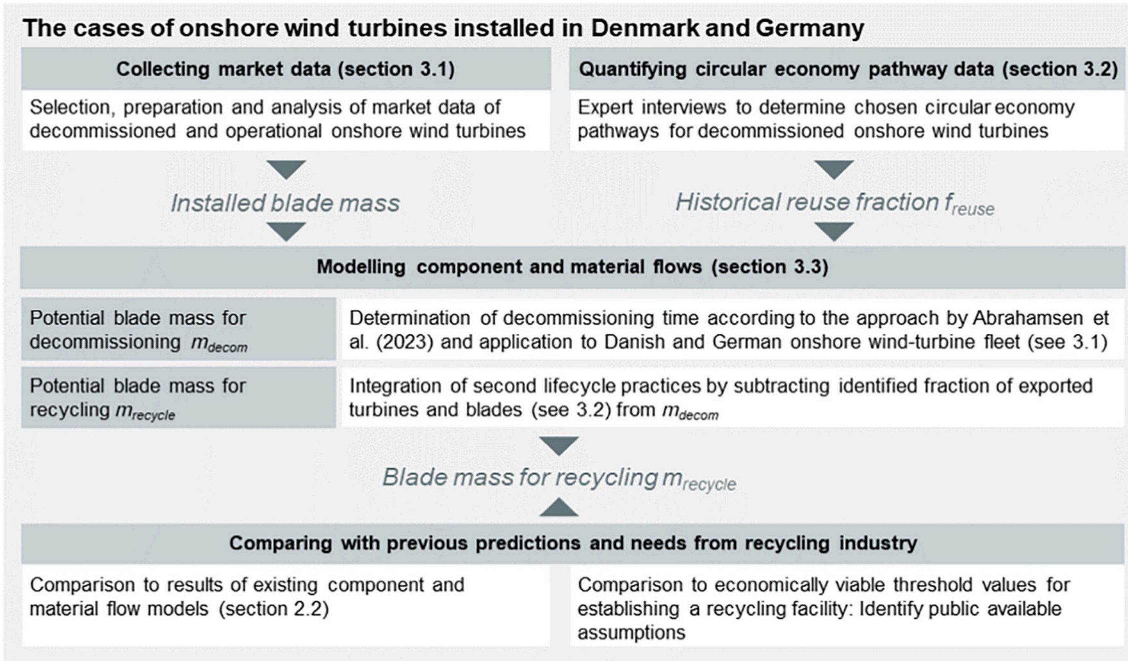

Fig. 2. Schematic overview of research methodology.

WindGuard, 2023). The German market register represents the operational turbines, and it is assumed that the operational fleet can approximate the installed turbine capacity by the in-operation capacity, as the amount of decommissioned turbines is small in relation to the total installed capacity. The data from Deutsche WindGuard (2023) and Lüers et al. (2023) are selected to display the decommissioning in Germany, the first providing aggregated decommissioning capacity per decommissioning year since 2000, the second presenting annual decommissioning capacity per installation year from 1995, based on Deutsche WindGuard's comprehensive market dataset.

The data extracts are filtered to onshore wind turbines, excluding small-scale turbines (below 25 kW for Denmark and below 50 kW for Germany), turbines with vertical rotors and offshore wind turbines. Information on the installation year, decommission year and rotor blade mass of the turbines is essential. The latter needs to be added to the original data extracts. For the market data extracts, information on the rotor diameter per turbine is available. Hence, the rotor blade mass is calculated using the regression function from Abrahamsen et al. (2023). For the decommissioned turbines in Germany, comprehensive information on the rotor diameters per turbine is missing, and therefore, an approximation of nine tonnes per MW is applied. Further details on the calculation of blade mass are provided in Supplementary information S2. The derived blade mass represents the total mass of the blades and does not further account for the use of different materials, such as glass fibre or carbon fibre. However, it can be assumed that turbines being decommissioned in the next ten years will mostly consist of glass fibre composites (Volk et al., 2021).

3.2. Determine chosen pathways of the decommissioned onshore wind turbines

Semi-structured interviews with experts are chosen as a qualitative research method to identify and quantify the chosen pathways of the decommissioned turbines and their blades in Germany and Denmark. Semi-structured interviews are an appropriate method for this study, as they are suitable for emerging research fields where there is a lack of empirical data (Nilsson, 2019, p. 687; Saunders et al., 2019, p. 444). In comparison, structured interviews would have made it easier to compare the interviews, while unstructured interviews would have supported the identification of new aspects (Döring and Bortz, 2016, pp. 369; 381). The method of semi-structured interviews balances the benefits of structured and unstructured interviews, as it makes it possible to integrate a theoretical understanding and guide the experts without excluding the experts finding new aspects (Gläser and Laudel, 2010, p. 37; Döring and Bortz, 2016, p. 372; Saunders et al., 2019, p. 437). The method therefore carries a lower risk of overlooking unidentified pathways from the theory or of missing experts having a different understanding of the object of the research. Moreover, it is important to understand the business activities of the experts in order to prevent quantified pathways from being counted twice when aggregating per country.

As structured data on pathways are not yet available, the scope of the data collection is to identify whether a second lifecycle is common or not in Denmark or Germany (refer to green area in Fig. 1). That said, the data aggregate the pathways in Fig. 1 to (i) a second lifecycle with the same function (R3-R6) and (ii) other waste-handing pathways (R7-R9, landfilling), where the blade can no longer function as such. The interview guideline is based on the theoretical understanding outlined in Section 2.1 and have been developed based on Gläser and Laudel (2010) by dividing questions related to an introduction (intro), assessing the suitability of the interviewee (filter) and key questions (key). Questions are formulated in a clear, simple, open and neutral way, allowing experts to answer in accordance with their knowledge, and limiting possible questioner bias (Gläser and Laudel, 2010, pp. 115; 131–142; Saunders et al., 2019, p. 447). Experts are considered suitable if they have completed at least one decommissioning project and have an overview of the decisions made in their company regarding the handling of decommissioned turbines. The interviews are about their involvement with the decommissioning and the handling of the decommissioned onshore turbines from Denmark and/or Germany. The minimum information required to be collected per interviewee is the number of handled decommissioned turbines and the ratio of taken pathways, detailed in:

- The fraction of resold turbines and their export and domestic share

- The fractions for the pathways taken by the wind turbine blades that were not sold as entire turbines, divided into
  - o the percentage of sold or kept blades with their export and domestic share, and
  - o the percentage that went into other waste handling (e.g. material recycling).

This enables the fraction of decommissioned turbines that enter a second lifecycle per country to be estimated. The guide is initially prepared in English and then translated into Danish and German. A more detailed summary of the questions and the final interview guide is provided in Supplementary information S3. A list of potential experts is prepared from information from national industry associations, through the networks of the authors, asking the interviewed experts for recommendations and an internet search. This leads to 21 potential interview partners for Denmark and 24 interview partners for Germany. Before conducting the interviews, the interview guide is tested with an industry expert. This contributes to the repeatability of the findings and the use of adequate terms in the interview guide (Döring and Bortz, 2016, p. 372). Interviews are preferred being conducted via video conference or in person, but are also accepted by telephone to increase the likelihood of the experts participating (Gläser and Laudel, 2010, p. 153). The process of conducting interviews is terminated when a major part of each market is covered. To ensure the trustworthiness of the derived number of handled turbines and the stated fraction of the pathways taken, the experts are asked for feedback, and the qualitative answers are analysed. For instance, the statement that "In the beginning, most of the turbines went to Eastern Europe. But in the last ten years, Italy and Ireland have nearly taken everything" confirms the interviewee's answer that decommissioned turbines were exported.

3.3. Component and material flows for planning blade-recycling capacity

This section introduces a new method of estimating the component and material flows of installed wind turbine blades for the planning of blade-recycling capacity in Denmark and Germany. As outlined in Section 2.2 and illustrated in Fig. 2, component and material flow models for recycling rely on two key assumptions: (i) the time of decommissioning, and (ii) considerations of circular economy pathways taken. The model proposed here builds on the method of Abrahamsen et al. (2023) for determining the time of decommissioning and, moreover, it integrates the derived empirical data on second lifecycle practices.

Abrahamsen et al. have analysed the Danish onshore wind-turbine fleet development and have described the decommissioning process of the initial blade mass m_0 installed at $t = 0$ by the blade mass removed per time unit $m_{decom}(t)$ as given by a Weibull function of the form

$$m_{decom}(t) = m_0 \bullet \frac{k}{\lambda}\left(\frac{t}{\lambda}\right)^{k-1} \bullet exp\left(-\left(\frac{t}{\lambda}\right)^{k}\right) \tag{1}$$

where t is the time after the initial installation year and the Weibull parameters k and λ are the shape and scale parameters (Abrahamsen et al., 2023). The two Weibull parameters can be related to the time where half of the installed blade mass $t_{½} = \lambda(ln2)^{\frac{1}{k}}$ has been decommissioned and to the time spread $\Delta t = \lambda\left(2.303^{\frac{1}{k}} - 0.105^{\frac{1}{k}}\right)$ from 10 % to 90 % decommissioning of the blade mass m_0 per installation year. For the Danish onshore fleet, Abrahamsen et al. (2023) derive a Weibull function of $\lambda = 30$ *years* and $k = 10$. This is based on the ratio between decommissioned and installed wind turbine blade mass for each installation year. In contrast, a 20-year lifetime is described by the Weibull parameters of $\lambda = 20$ *years* and $k = 70$, which results in $\Delta t = 0.9$ *year* (Abrahamsen et al., 2023). This approach is elaborated in this paper for the Danish and German onshore wind-turbine markets by fitting an accumulated Weibull function $F(t) = 1 - exp\left(-\left(\frac{t}{\lambda}\right)^{k}\right)$ to the ratio between decommissioned and installed blade mass as function of the age of the turbines. Compared to other studies (see Section 2.2), this approach therefore takes more extensive data – historical decommissioning and operational data – into account and does not rely only on historical decommissioning data or static assumptions.

The influence of a second lifecycle on the potential blade mass for recycling in a country $m_{recycle}(t)$ is that the predicted decommissioning blade mass of Eq. (1) will be reduced by the fraction of reused blades f_{reuse}:

$$m_{recycle}(t) = f_{reuse} \bullet m_{decom}(t) \tag{2}$$

Thus, one can use Eq. (2) to estimate the blade mass expected for recycling in a country, assuming that the reused turbines are exported. If the turbines remain in the country, the total expected blade mass for recycling in that country equals the total blade mass being decommissioned in that country, but the year in which they enter the recycling stream would be delayed. This approach is in line with the few existing studies that have recognised circular economy pathways (Andersen et al., 2016; Pehlken et al., 2017; Tota-Maharaj and McMahon, 2021). For instance, Andersen et al. (2016) expect that a fraction of the decommissioned turbines will be reused in the country under study for a certain period of time and that domestic recycling will be delayed accordingly. In another scenario, they assume that exported turbines will not enter the domestic recycling path. For the purpose of this study, the figures for the fraction of reuse within the country are neglected, as shown in Eq. (2). Otherwise, a tracing of each turbine beyond the decommissioning company would be necessary, and such a system does not currently exist. These turbines are probably still in their second lifecycle, so historical data is only available to a limited extent, and whether the turbines or their blades would then enter a third lifecycle has not yet been explored. Also, the possible reimport after a second lifecycle for end-of-life treatment is unlikely to affect Eq. (2). This is due to the current regulation of cross-border movements of waste that make import complex and expensive to carry out, among others as an EAK waste code for blade composites is missing (The European Parliament and The Council of the European Union, 2006).

The input variables $m_{decom}(t)$ and f_{reuse} of Eq. (2) are based on historical data and the experience of the interviewed experts. To account for the possibility that these findings may not apply in the future, a range of future expected blade masses is defined:

- "Maximum domestic recycling scenario", $m_{decom}(t)$: Assumes that no secondary market exists anymore, and thus 100 % of the expected decommissioning could enter the domestic recycling stream without a time delay.
- "Minimum domestic recycling scenario", $m_{recycle}(t)$: Foresees that the second lifecycle practices that took place in the past will continue in the future.

The results are compared to the prediction according to the assumptions made by most studies of a static decommissioning time of 20 years and neglecting a second lifecycle (see Section 2.2), hereafter referred to as "20-year scenario". Moreover, to put the derived estimates into perspective for the planning of blade-recycling infrastructure, a threshold for establishing a new blade-recycling facility is set at 5000–15,000 tonnes per year. This is justified as publicly available assumptions vary between a minimum of 5000–15,000 tonnes per year for a new blade-recycling facility in Europe (see Table 1).

4. Results

The results section first presents the decommissioned and operational onshore wind turbines and their corresponding blade masses located in Denmark and Germany (Section 4.1). This is followed by outlining the interview results of the determined and chosen circular economy pathways of decommissioned onshore wind turbines in the

Table 1
Overview of assumptions for a blade recycling facility, based on Villadsen, 2023; Ricard, 2023; Schmid et al., 2020; Zotz et al., 2019; Andersen et al., 2016; RenerCycle, 2023.

Source	Annual blade mass for operating a blade-recycling facility
Villadsen, 2023	State 10,000–15,000 tonnes per year as the minimum amount for establishing a pyrolysis plant for glass fibres in Denmark.
Ricard, 2023	For cement co-processing to be established in Denmark, 12,000 tonnes per year are quoted as a threshold.
Schmid et al., 2020	A co-cement processing facility in northern Germany was operated with 15,000 tonnes/per year, 10,000 tonnes coming from blades. The minimum amount to operate economically is not specified.
Zotz et al., 2019	Neocomp was able to prepare up to 25,000 tonnes of processed materials per year for cement co-processing with one machine, of which around 5000 tonnes of glass fibres came from rotor blades
Andersen et al., 2016	Quote 5000–6000 tonnes per year for producing a filler for cement production.
RenerCycle, 2023	Quote an annual capacity of 6000 tonnes for their blade recycling facility, relying on heat treatments, to be located in northern Spain

respective markets (Section 4.2). Finally, based on the inputs from Sections 4.1 and 4.2, predictions of expected recycling blade masses for planning blade-recycling capacity in Denmark and Germany are provided (Section 4.3).

4.1. Onshore wind turbines in Denmark and Germany

The wind markets in Denmark and Germany have several similarities. For instance, both markets are mature with a wide variety of turbine types installed, mostly from national manufacturers (Danish Energy Agency, 2022; Bundesnetzagentur, 2023). Also, their electricity markets are interconnected (Nord Pool AS, 2024), and both counties have limited sites available for wind energy projects (Ziegler et al., 2018). Historically, the absolute numbers of installations and decommissions have differed in the two countries, although both markets have a long history, with the first onshore wind installation in 1977 for Denmark and in 1983 for Germany, as illustrated in Fig. 3. Fig. 3 also shows the blade mass of the operational and decommissioned turbines as determined from the rotor size of the turbines or, if not available, through the average blade mass per capacity (see Section 3.1).

As of 31/01/2022 (Danish Energy Agency, 2022), Denmark had 4711.9 MW installed capacity in land-based operations, represented by 4186 turbines and 51,016.2 tonnes of blade mass. The average age of the operational turbines is 20.9 years. 73.5 % of operational turbines reached or exceeded the 20-year design lifetime (International Electrotechnical Commission, 2019). The fraction of turbines older than the design lifetime is 39.7 % and 29.6 % based on installed capacity and blade mass respectively. Decommissioning has taken place since 1998, totalling 826.4 MW, which corresponds to 3195 turbines and 7130.8 tonnes of blade mass. The average age of the decommissioned turbines is 18.0 years. The year 2002 represents 36.7 % of total decommissioned wind turbines. The peak is not as extreme when looking at the decommissioned capacity (13.3 %), as the size of the turbines has increased over time, and in 2002 it was mostly turbines below 150 kW that were decommissioned. One major driver was the *skrotpræmie*, a support scheme that incentivised the decommissioning of wind turbines up to 150 kW from 1999 to 2003 (Klima-, Energi- og Forsyningsministeriet, 2001). In general, decommissioning has fluctuated highly in recent decades, with an annual average of 297 tonnes of blade mass and a standard deviation of 258 tonnes. In the last three years, 2019–2021, only 117 turbines were decommissioned, though this represented 18.1 % of the total decommissioned blade mass. Overall, a blade mass of 57,915.7 tonnes has been installed that is either in operation or has been decommissioned.

As of 30/06/2023 (Bundesnetzagentur, 2023), Germany had 59,231.0 MW installed capacity in land-based operation, represented by 28,611 turbines and 738,718.6 tonnes of blade mass. The average age of the operational portfolio is 14.5 years. 29.4 % of total operational turbines are 20 years or above. The fraction of turbines older than the design lifetime is 14.8 % and 10.7 % based on installed capacity and blade mass respectively. Decommissioning started around 2000, totalling ~3600 MW (Deutsche WindGuard, 2023) and ~32,400 tonnes of blade mass, assuming 9 tonnes per MW. This amounts to ~4500 decommissioned turbines when approximating allowing 0.8 MW per turbine, which is the average capacity of the decommissioned turbines according to the market register (Bundesnetzagentur, 2023). Peaks can be observed in Fig. 3 in 2014 (~350 MW) and 2017 (~500 MW). Also, in Germany, decommissioning has fluctuated greatly, with an annual average of ~1400 tonnes of blade mass and a standard deviation of ~1250 tonnes. A peak was expected in 2021 as onshore turbines with a fixed feed-in were phased out (Zotz et al., 2019; Volk et al., 2021). Nevertheless, only marginal decommissioning took place in 2021 as market electricity prices rose significantly (Netztransparenz, 2023).

In both markets, annual decommissioning and installation rates have fluctuated greatly in recent decades. 32,797 turbines with approximately 790,000 tonnes of total blade mass are operating in Denmark (6 %) and Germany (94 %) which will enter different pathways after decommissioning, either in the domestic market or abroad.

4.2. Chosen pathways of decommissioned onshore wind turbines in Denmark and Germany

Interviews on the chosen pathways after decommissioning onshore wind turbines in Denmark and Germany were conducted with 16 experts. The interviews lasted 45–120 min and occurred from 21/09/

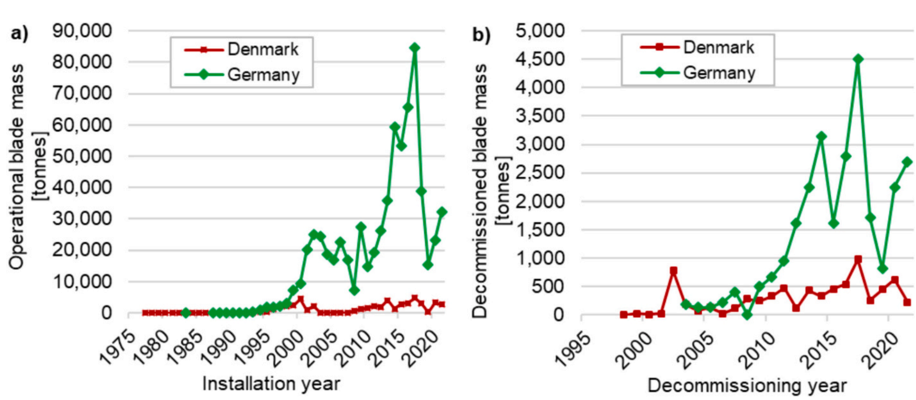

Fig. 3. Historic development of onshore turbine blade mass that is (a) currently operating and (b) has been decommissioned in Denmark and Germany. Analysis based on Danish Energy Agency (2022); Bundesnetzagentur (2023); Deutsche WindGuard (2023).

2023–05/02/2024. 37.5 % of the experts covered Denmark, 43.75 % Germany and 18.75 % covered both markets. The experts' positions vary, though all are involved in handling the decommissioned turbines: 28.6 % of the experts are Managing Directors, 14.3 % are Project Managers, 9.5 % are Heads of Sustainability and the remainder (47.6 %) are in other positions. Also, the type of company differs across the experts, original equipment manufacturers (OEM) (18.75 %), project developers and operators or service providers (18.75 %), and decommissioning companies with or without their own recycling capabilities (62.5 %) participated. Detailed information about each interview is displayed in Table S1 in Supplementary information S4.

A common finding across the interviews is the number of handled turbines that are used as the basis to quantify an aggregated split of the taken pathways. The stated percentages for the taken pathways are multiplied by the number of handled turbines of the respective company and aggregated across all interviews. The aggregate is put in relation to the overall quantity of decommissioned turbines in the two countries: 3195 decommissioned turbines in Denmark and 4500 turbines in Germany (see Section 4.1). Nine experts cover the Danish decommissioning market with market shares below 1 % and up to ~25 %. The German market is addressed by ten experts with market shares between below 1 % and ~22 %. To avoid double-counting, service and manufacturing companies that hired a decommissioning company are discarded when the decommissioning company is interviewed or is not known; interviews from those experts are not included in the calculation (see Supplementary information S4). Overall, the experts covered roughly 2100–2200 decommissioned turbines from Denmark, hence ~65–69 % of the total decommissioned turbines. For Germany, ~49–51 % of the market was addressed by the interviews, as the experts have handled roughly ~2220–2300 decommissioned turbines. Consequently, a major part of each market is covered.

Fig. 4 presents the aggregated splits of pathways taken by interviewees in (a) Denmark and (b) Germany. The results for Denmark show that ~61 % of the turbines were exported for a second lifecycle (R3-R6), ~59 % as entire turbines and ~1.7 % as spare parts. In Germany, ~48 % of turbines were exported in their entirety (~46 %) or the blades were exported as spare parts (~2 %). In both countries, the number of blades that stayed in the country as spare parts were minimal, ~0.8 % in Denmark and ~2 % in Germany. Other waste handling accounted for ~38.5 % for Denmark and ~50 % for Germany.

To ensure the trustworthiness of the findings, the experts were asked for feedback. Interviewees covering the German market sent feedback; for Denmark also, the majority provided written feedback. Special emphasis was placed on the interviewees with major market shares; the authors of this study called for a response or investigated publicly available information. It should be noted that, for the earlier decommissioning, uncertainties exist because not all experts precisely remembered the entire history of their activities, nor had they filed it in a data system.

To assess how sensitive the derived fractions are to the pathways taken by the turbines not covered by the interviews, it is assumed that these turbines were either all sent into waste-handling or all exported for a second lifecycle. For Denmark, where ~31–35 % of the turbines are not covered by the interviews, the fraction of exported blades for a second lifecycle as entire turbines or spare parts (f_{reuse}) would range from 40 to 74 %. In Germany, the absolute number of decommissioned turbines covered by the interviews is similar to that in Denmark. Since 1305 more turbines have been decommissioned in Germany than in Denmark, it leads to ~49–51 % of the total decommissioned turbines being not covered by the interviews. For those turbines that were either sent completely into waste-handling or were all exported, f_{reuse} ranges from 24 to 74 %.

Moreover, other sources were sought in order to compare them with the order of magnitudes determined in this study: Ricard (2023), for instance, indicates a reuse fraction of 50 % or more for Denmark. Also, information from Danish blade landfilling shows that the study's results are in a reasonable order of magnitude (Energi Watch, 2020; Danish Energy Agency, 2022; From and Dohm, 2022) (see Supplementary information, S5 for more details). For Germany, it is mentioned in one study that the reuse fraction has a relevant share, though without quantifying it (Kühne et al., 2022). In another study, one company is cited with a reuse share of ~10 % without stating the company's market share (Bundesverband WindEnergie e.V., 2019). The magnitude of ~10 % is also reported by one of the interviewees covering Germany. However, some experts have also stated reuse fractions towards 100 % for their covered turbines. Also, the assumption by Pehlken et al. (2017) that only turbines below the design lifetime of 20 years are exported for reuse is not confirmed by the experts interviewed for this study.

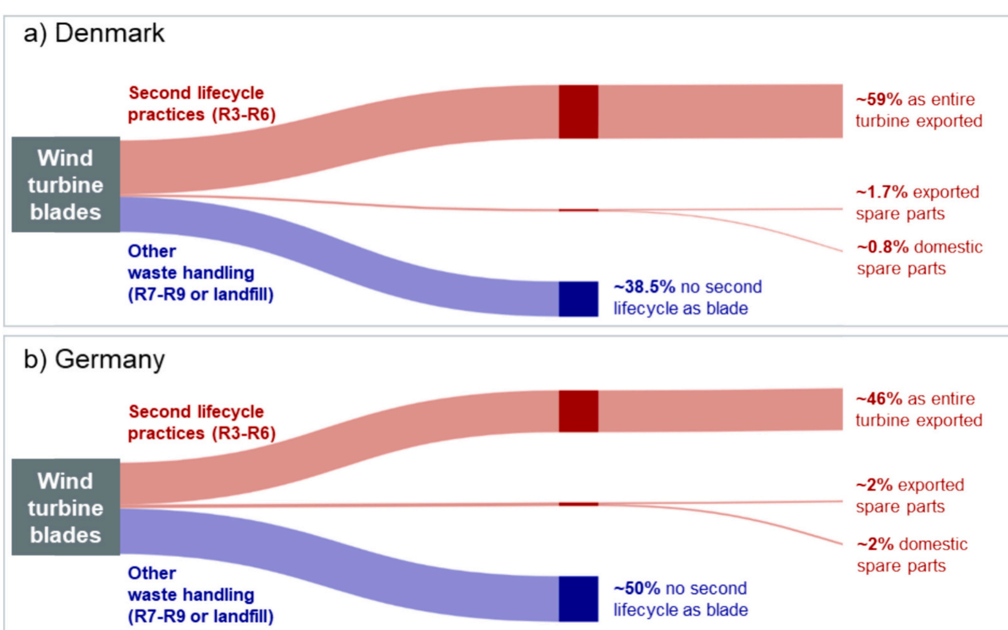

Fig. 4. Pathways of blades from decommissioned onshore wind turbines in Denmark (a) and Germany (b) based on conducted interviews. Graphs prepared with www.sankeyart.com.

This study discovered that a second lifecycle for Danish and German onshore wind turbines was common: f_{reuse} for Denmark corresponds to an order of magnitude of ~60 %, and for Germany of ~50 %.

4.3. Component and material flows for planning blade-recycling capacity in Denmark and Germany

Applying the method introduced in Section 3.3, first, the Weibull parameters k and λ are determined for calculating the expected decommissioning according to Eq. (1), followed by applying f_{reuse} of Denmark and Germany (see Section 4.2) to Eq. (2).

Fig. 5 shows the results of fitting accumulated Weibull functions to the ratios between decommissioned and installed blade mass per installation year for Denmark and Germany.

For Denmark, the accumulated Weibull function (blue line) has the parameters $\lambda = 29.79\,years \pm 0.25$ and $k = 9.11 \pm 0.88$, i.e. similar parameters as shown in Abrahamsen et al. (2023). For the fitting, data points of an age of 2, 17–19 (shown as dashed red line in Fig. 5) have been removed from the fit since the number of installed turbines was very small in those years, resulting in a large depletion. Also, turbines above the age of 35 years are disregarded, as these were installed before design standards for wind turbines existed (see Abrahamsen et al. (2023) for details). In contrast to Denmark, a shorter history is available for Germany. Moreover, the available data for Germany only provides ratios until 1995, and therefore, data for 1983–1994 are lacking (Lüers et al., 2023). Currently none of the ratios per installation year (green line) have reached 100 %, hence a full decommissioning of an installation year. Instead at 1995–1997, the ratios settle at around ~37–38 %, i.e. 61–62 % of the turbines with ages of 25–27 years are still in operation. This flattening could be interpreted in different ways. For instance, it could indicate that a fraction in the order of magnitude of ~62–63 % of installed turbines have lifetime extensions. In contrast to Denmark, Germany requires an external assessment when the design lifetime of a turbine is reached (Ziegler et al., 2018), which could explain different market behaviour. Another explanation could be that it is due to a lack of available data, and that going forward, with a longer history becoming available, the ratios would increase. For now, data points for 1998–2022 are used for the fitting that results in the parameters for Germany's Weibull function 1 (pink line) of $\lambda = 25.83\,years \pm 0.18$ and $k = 7.49 \pm 0.34$. The error bars of the provided parameters are relatively small. To understand the influence of including a further data point, here in 1997, the parameters for the Weibull function 2 (brown line) are also shown in Fig. 5. Accordingly, the scale parameter would be reduced slightly to $\lambda = 25.10\,years \pm 0.12$, and the shape parameter would increase slightly to $k = 8.71 \pm 0.29$. In comparison to Denmark, the shape parameter is relatively similar, but the scale parameter for Germany shows that decommissioning takes place slightly earlier in Germany than in Denmark. In Denmark, operation lasts 29 years before half of the onshore wind-turbine fleet might be decommissioned and in Germany 25 years. Finally, an overview of the input parameters for calculating $m_{decom}(t)$ and $m_{recycle}(t)$ through Eqs. (1) and (2) is provided in Table 2.

As outlined in Section 3.1, according to the DEA, as of 31/01/2022 installed onshore wind turbines are used in Denmark, while for Germany, the installed onshore wind turbines are calculated by means of the operational onshore wind-turbine fleet according to the MaStR as of 30/06/2023. The results of applying the input parameters to Eqs. (1) and (2) are the ranges of the annual expected domestic recycling blade mass of onshore wind turbines in Denmark (Fig. 6) and Germany (Fig. 7). These are compared to a "20-year scenario" and actual decommissioning. The shown decrease in blade mass by 2065 is due to the fact that new installations are not considered. Moreover, to

Table 2
Overview of input parameters for Eqs. (1) and (2), based on DEA (2022) and Lüers et al. (2023) for Eq. (1) and on conducted interviews for Eq. (2).

Scenario	Eq. (1), parameters for Weibull function	Eq. (2), assumption for f_{reuse}
20-year scenario	20 years	$f_{reuse} = 0$
Maximum domestic recycling scenario	• Denmark: $\lambda = 29.79\,years$ and $k = 9.11$ • Germany: $\lambda = 25.83\,years$ and $k = 7.49$	$f_{reuse} = 0$
Minimum domestic recycling scenario		• Denmark: $f_{reuse} = 0.6$ • Germany: $f_{reuse} = 0.5$

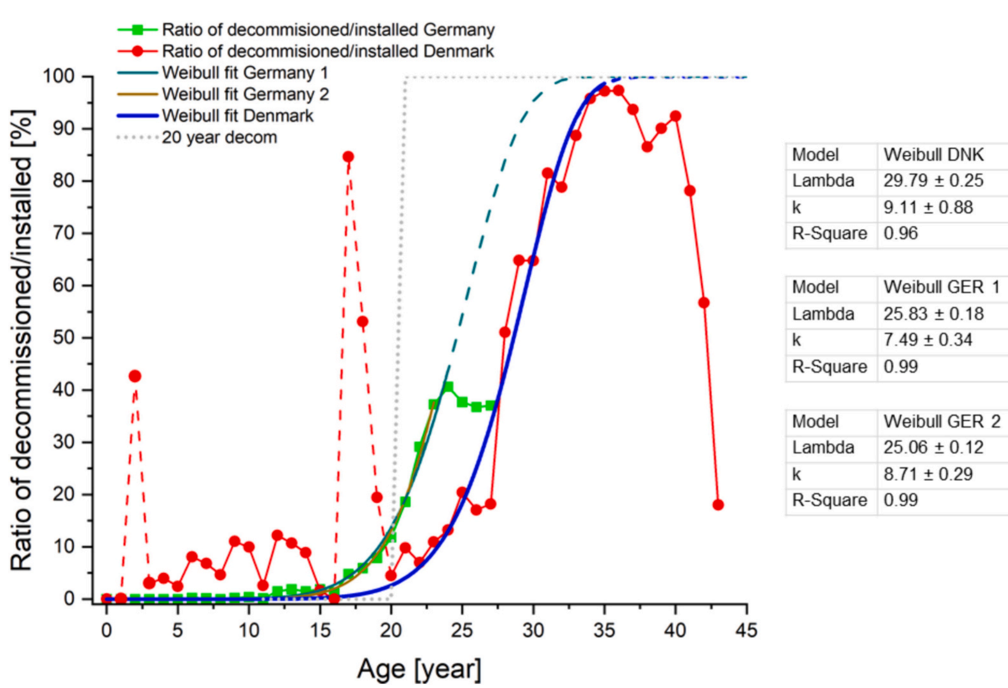

Fig. 5. Accumulated Weibull functions representing Denmark's and Germany's ratio between decommissioned and installed blade mass, in comparison to a 20-year lifetime. Analysis inspired by Abrahamsen et al. (2023) and based on DEA (2022) for Denmark and on Lüers et al. (2023) for Germany.

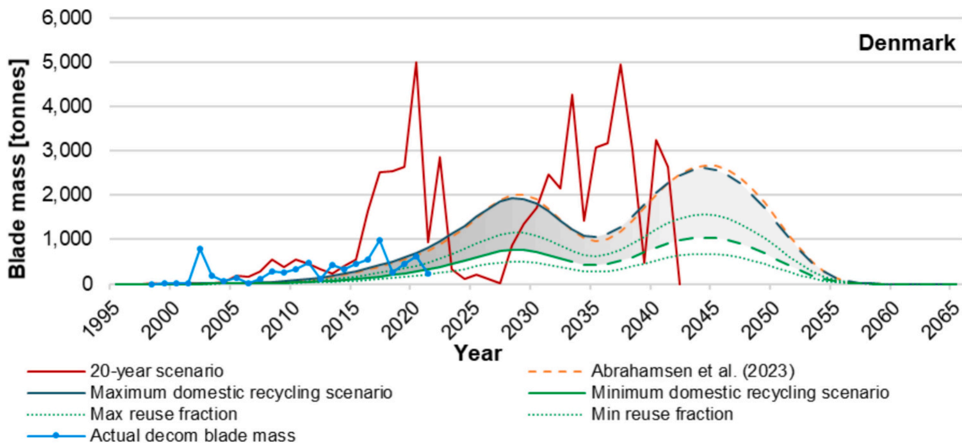

Fig. 6. Range of expected domestic recycling blade mass of installed onshore wind turbines in Denmark in comparison to the "20-year scenario", existing literature and actual decommissioning. Analysis based on Eqs. (1) and (2); DEA (2022); Abrahamsen et al. (2023).

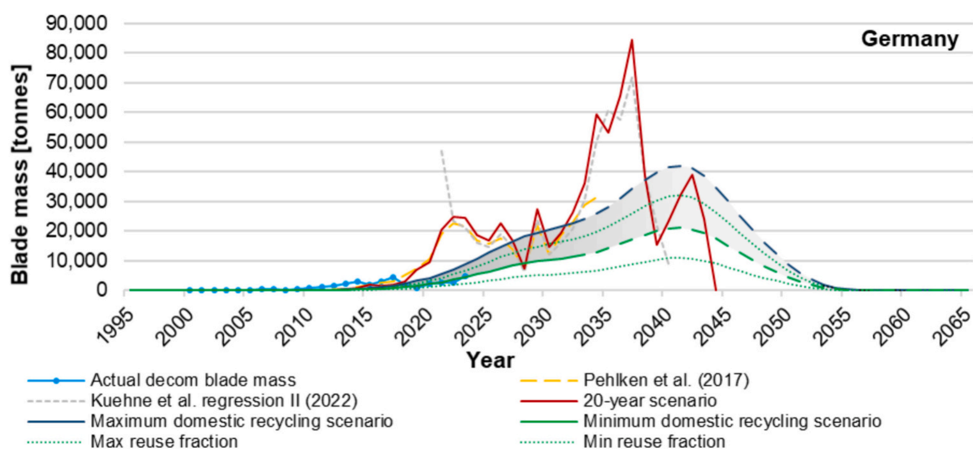

Fig. 7. Range of expected domestic recycling blade mass of installed onshore wind turbines in Germany in comparison to the "20-year scenario", existing literature and actual decommissioning. Analysis based on Eqs. (1) and (2); Bundesnetzagentur (2023); Pehlken et al. (2017); Kühne et al. (2022); Deutsche WindGuard (2023).

acknowledge that prediction uncertainties increase with a wider timespan, the range of blade mass is illustrated for the later years with a dashed line.

Fig. 6 shows the results for Denmark. The "20-year scenario" roughly follows the installation of each year as shown in Fig. 3, but postponed by 20 years. In some years prior to 2016, the actual decommissioning and the "20-year scenario" are quite similar. However, from 2016 onwards they diverge strongly. It becomes apparent that many onshore turbines are not decommissioned after 20 years on average and instead are operated beyond a design lifetime of 20 years. It seems that actual decommissioning corresponds more closely to the expected decommissioning according to the derived Weibull function (see Fig. 5) represented by the "Maximum domestic recycling scenario". This is in line with the findings by Abrahamsen et al. (2023). In the "Minimum domestic recycling scenario", a secondary market with $f_{reuse} = 0.6$ would reduce the total installed blade mass of 57,915.7 tonnes to 23,166.3 tonnes. Neither scenario fluctuates as much as the "20-year scenario", and the blade mass is distributed over a longer time period. In the next ten years, the annual blade mass will range between ~950–1900 tonnes (maximum scenario) and between ~380–770 tonnes (minimum scenario). A comparison of the results with threshold values of 5000–15,000 tonnes per year for investments in new recycling plants shows that these thresholds are not reached in any present scenario.

Fig. 7 visualises the results for Germany. An absolute increase in yearly blade mass to be decommissioned is expected across all scenarios. The forecasts from Kühne et al. (2022), Pehlken et al. (2017) and the "20-year scenario" roughly follow the annual installation numbers with a time delay of 20 years (see Fig. 3). The high peak in 2021 from Kühne et al. (2022) is due to the assumption that every turbine still operating and older than 20 years would be decommissioned in the first year of their prediction. However, actual decommissioning volumes show that most onshore turbines are not decommissioned after 20 years. Instead, they indicate something more akin to the derived Weibull function (see Fig. 5), with many turbines operating beyond a design lifetime of 20 years. The annual blade mass in the "Maximum domestic recycling scenario" ($f_{reuse} = 0$) and "Minimum domestic recycling scenario" ($f_{reuse} = 0.5$) do not fluctuate as much and are shifted into the future. A secondary market with a similar export rate as in the past would reduce the total blade mass of 738,718.6 tonnes to 369,360 tonnes of the operating turbines. In the next ten years, annual blade mass ranges between ~8900–22,600 tonnes (maximum scenario) and between ~4400–11,300 tonnes (minimum scenario). Hence, the threshold values of 5000–15,000 tonnes per year for a new recycling plant are partially exceeded in the next ten years in the "Minimum domestic recycling scenario" ($f_{reuse} = 0.5$) and surpassed in the "Maximum domestic recycling scenario" ($f_{reuse} = 0$). For instance, in the case of a neglectable secondary market, 10,000 tonnes per year are first exceeded in 2024. The "20-year scenario" was forecasted to surpass in 2021 and in the case of a secondary market in the magnitude of the past it is forecasted six years later, in 2030.

5. Discussion

The study shows that second lifecycle practices have been common and that wind turbines from Denmark and Germany were mostly exported to other European countries, therefore slowing down the resource use and hence reducing the consumption of virgin materials. Moreover, after no structural value remains (i.e. potentially after multiple lifecycles), the materials of the wind turbines could enter the recycling pathways predominately in Europe. This is of particular interest for materials with high dependencies in sourcing from countries outside Europe, e.g. rare earth materials or manganese (Rystad Energy, 2023, p. 23), as material recycling could improve Europe's self-sufficiency (European Commission, 2023b). Also, for manufacturing new blades, the use of virgin materials can be reduced when sustainable recycling technologies for composites become market mature. With major European companies being committed to a landfill ban and fully recyclable blades (Kramer and Beauson, 2023), announcements to establish large-scale mechanical recycling or energy recovery have taken place in Europe (WindEurope, 2021; Windkraft-Journal, 2023). No overcapacity should be created at energy-recovery facilities, because once blades haven taken this route, they are lost for material recycling. To plan blade recycling, this study has shown that the blade mass for recycling ($m_{recycle}$) in Denmark and Germany could be postponed and being significantly lower than estimated in previous studies, as Figs. 6 and 7 show, hence different timings of the threshold values for operating a blade-recycling facility economically are met. It is recommended to further explore the economic scalability and environmental impact of recycling solutions like pyrolysis, solvolysis and mechanical recycling, as they may differ on a project basis. Empirical studies of the different recycling technologies should cover different facility sizes and regions and assess (i) expected investment and operating costs, (ii) the potential revenues of the recycled materials and (iii) the environmental impact. A comparison of these results in the context of the current economically available technology of cement co-processing would provide valuable insights and could encourage policymakers to promote them accordingly. For example, governments could support research and development projects on modular and scalable recycling technologies financially to enable economic viability with smaller quantities.

The results are of relevance in a European context, as Denmark and Germany represent a majority of the 7.2 GW of decommissioned wind turbines in Europe to date (Danish Energy Agency, 2022; Deutsche WindGuard, 2023; WindEurope, 2023). Going forward too, Germany particularly will have a significant share of the expected decommissioning (WindEurope, 2020, p. 12): WindEurope estimates that 25,000 tonnes will enter waste-handling in 2025 and 52,000 tonnes in 2030, mostly from Germany, followed by Spain and also some from Denmark. On the one hand, other countries can learn from these mature markets, i.e. how Denmark will handle low expected volumes and Germany a steadily increase. On the other hand, transferring the paper's methodology to other markets could improve their blade mass forecasts, e.g. as significant reuse was mentioned for Europe (Graulich et al., 2021) and Norway (Andreassen, 2023). Moreover, the realistic planning of component and material flows is also relevant for several other industries (e.g. automotive, photovoltaic) (Jensen et al., 2020; European Commission, 2020; Kara et al., 2022). As this paper's methodology follows an industry-neutral framework of R-principles, it can be applied to other industries. For instance, in the fast-growing photovoltaic and battery markets with high technological progress, reliable forecasts are currently missing, as are explorations of second lifecycles (Reinhardt et al., 2019; Franco and Groesser, 2021).

The component and material flow models for the installed onshore wind turbines in Denmark and Germany rely on assumptions for (i) the time of decommissioning and (ii) second lifecycle considerations that are based on the state of the art and newly collected data.

First, it should be noted that historical data are still relatively limited, even for Denmark, which has the largest available history worldwide. For Germany, the available data history reflects only 25 years, making the model for Germany less reliable than the Danish model. Consequently, when a longer data history becomes available, the models' reliability improves. At present, only the German market register is regularly updated, so that a continuous update of the component and material flow model is possible, which is recommended for future research. In addition, further data features could be included in the market registers in order to improve the data quality of the input variables for the component and material flow models. For instance, if the blade mass per installed wind turbine is added, then this information does not have to be added with a regression function based on the rotor diameter of each turbine or by calculating based on the installed capacity. Nevertheless, the approach introduced here already now provides more reliable forecasts, as it considers historical data on both installed and decommissioned turbines. It therefore contrasts with studies that have calculated the time of decommissioning only on the basis of historical decommissioning numbers or assumed a static time (e.g. Lichtenegger et al., 2020; Kühne et al., 2022). This is shown by the study's results presented for Denmark and Germany, as expected decommissioning (m_{decom}) more accurately represents actual decommissioning than assuming decommissioning after a lifetime of 20 years. Going forward, the time of decommissioning could, for instance, be affected by new regulations, e.g. easing the permitting process of repowering projects. The impact of economic incentives is also visible in the historical data: Denmark subsidised decommissioning from 1999 to 2003, which led to a significant decommissioning in those years. Another example is the procedures for lifetime extensions beyond the design lifetime of 20 years. An effect is eventually made tangible when comparing the derived Weibull functions of Denmark and Germany: In contrast to Denmark, where annual inspections are carried out within the standard maintenance routine, Germany legally requires an external-audited assessment on the structural stability of the wind turbine to allow it to operate beyond its design lifetime (Ziegler et al., 2018). This could explain the slightly earlier time of decommissioning in Germany in comparison to Denmark. Nevertheless, further explorations of the different influencing factors for repowering and lifetime extensions and their interlinkages are necessary.

Secondly, data on which pathways were taken after decommissioning wind turbines were not available prior to this study. Even though the historical reuse fraction for Denmark collected here could in theory vary between 40 and 74 % (refer to dotted green lines in Fig. 6) and for Germany between 24 and 74 % (refer to dotted green lines in Fig. 7), an order of magnitude of ~60 % for Denmark and ~50 % for Germany is identified that was cross-checked with other sources (see Section 4.2). Studies of other industries also identify significant reuse rates, e.g. 55 % of hybrid vehicles from Japan and 70 % of their batteries were reused abroad (Wang et al., 2020). The study shows that it is crucial to integrate second lifecycle considerations into the planning of blade-recycling capacity. As such, Eq. (2) was introduced to reflect the fraction of decommissioned blade mass entering a second lifecycle and the remainder being potentially available for recycling (i.e. pyrolysis, mechanical recycling, solvolysis) in the respective country. In reality, it could, however, also enter another waste-handling pathway such as energy recovery (e.g. cement co-processing). The fraction of turbines and their blades entering a second lifecycle could vary in the future, which is accounted for in the component and material flow models by showing a range between m_{decom} and $m_{recycle}$. The majority of the experts interviewed believed that with increasing blade sizes an economically viable export becomes difficult to realise. Additionally, they expected the supply of decommissioned turbines to surpass the demand for second-hand turbines and blades. Thus, steadily decreasing f_{reuse}; for Germany some experts stated a magnitude of 10–30 %, which would lead to larger domestic recycling blade mass. In contrast, the experts mentioned that demand for reused spare parts is increasing in order to secure spare parts that are not manufactured anymore, indicating a tendency to hibernation. For comparison, studies of mobile phones have shown low return rates due to hibernation and a lack of awareness of possible routes (Wilson et al., 2017; Inghels and Bahlmann, 2021; Prabhu and Majhi, 2023). Moreover, second-hand markets could further accelerate as from 2026 onwards production capacity bottlenecks are expected for all major components and the assembly of wind turbines in Europe (Hutchinson and Zhao, 2023; Rystad Energy, 2023). In light of this, going forward, new policies could also be announced that promote structural reuse by introducing tender requirements similar to those for material recycling (Danish Energy Agency, 2024) and ensuring adequate decommissioning practices.

The main assumptions of the study have been discussed throughout this section and result in the following limitations to the research objectives. The first research objective was to identify whether giving a second lifecycle to wind turbines and their blades has been a common practice. Through the developed interview process, it was possible to determine that a significant share of the turbines or their components were kept or sold. To increase the certainty that the decommissioned turbines or their components have entered a second lifecycle, the end-user should also be interviewed. Moreover, the entire market was not covered throughout the interviews, and some experts influenced the aggregated results heavily due to their significant market shares. Nevertheless, by analysing the two countries, checking alternative sources and doing sensitivity checks, it can be concluded that the order of magnitude of turbines that entered a second lifecycle was significant. The second research objective was to provide a more reliable forecasting method for planning domestic blade-recycling capacity that was evaluated through its application to Denmark and Germany. The models were evaluated on the basis of actual decommissioning data, but market data on actual recycling were not available. Moreover, an evaluation of the method took place by assessing existing studies of other regions and industries. Furthermore, as discussed above, another limitation is that the proposed models are based on a limited history and a set of data features that could fall short of forecasting future developments and more complex market dynamics, e.g. the effects of regulatory changes. To account for this uncertainty, a wide range of $m_{recycle}$ and m_{decom} was used, which led to a relatively wide range of expected blade masses for recycling. The third objective was to forecast expected annual blade masses of installed onshore wind turbines in Denmark and Germany and to assess the likelihood that threshold values for establishing economically viable blade-recycling facilities will be met within the next ten years. Through the uncertainties of the input variables of the component and material flow methods, outlined above, uncertainties also exist for assessing whether threshold values are likely to be met in the respective countries. If other threshold values prove more applicable in the future, Figs. 6 and 7 show the estimated annual blade mass, so readers can identify the year in which a different threshold would be first exceeded. Furthermore, the material flows for composite recycling from the manufacture and operation of onshore wind turbines, end-of-life offshore wind turbines and other industries (e.g. construction, automotive or aerospace) were not within the scope of this study, but should be considered to assess whether the thresholds for new composite recycling facilities will be met in Denmark and Germany.

6. Conclusions

This paper quantifies the taken pathways of decommissioned onshore wind turbines and integrates this into a component and material flow model for planning blade-recycling capacity, using the example of Denmark's and Germany's onshore wind turbine fleet. For both countries, a second lifecycle of wind turbines abroad has been identified by performing expert interviews, and reselling turbines for a second lifecycle is for Denmark approximately 60 % and for Germany 50 %. If turbines are not sold, the fractions of blades being sold or kept as spare parts are relatively small (2.5–4 %), and the remainder enters other waste-handling pathways. The order of magnitude for a second lifecycle of wind turbines and their blades abroad shows that it affects the expected component and materials flows when planning blade-recycling capacity. Surprisingly previous forecasts of waste-handling have widely ignored the export of turbines. The expected blade mass for the recycling of installed onshore wind turbines in Denmark and Germany is calculated assuming that the time of decommissioning depends on the historical ratios of decommissioned over installed blade mass per installation year and by integrating the collected empirical data about the chosen circular economy pathways, leading to the following forecasts:

- Denmark: In the next ten years, ~950–1900 tonnes per year of blade mass is expected to be decommissioned. So far, approximately 60 % of decommissioned onshore turbines had a second lifecycle abroad. If continued in the future, this would lead to ~380–770 tonnes per year for the domestic recycling industry.
- Germany: Expected decommissioning is steadily increasing with ~8900–22,600 tonnes per year of blade mass in the next ten years. Historically, approximately 50 % of decommissioned turbines were exported for a second lifecycle. If applicable in the future, ~4400–11,300 tonnes per year would potentially enter the blade-recycling stream in the next ten years.

This study referred to threshold values of 5000–15,000 tonnes per year for a new blade-recycling facility. Denmark, on its own, would not surpass this threshold with the currently installed onshore turbines, highlighting the need for a multi-national approach and for aggregating from the offshore wind industry or other industries. Cross-industry standards (e.g. common EAK waste code) and multi-national legislation easing cross-border movements would support this. The German fleet will reach most of its thresholds within the next ten years; for instance, 10,000 tonnes per year will be first exceeded between 2024 and 2030. Further research on the reasons for decommissioning turbines and the choice of pathway for them will improve predictions by narrowing the range of blade mass and, therefore, specifying the time window when economic threshold values are likely to be reached. Next to planning recycling capacity, the capacity for sustainable decommissioning and second lifecycles should be assessed in future research. For instance, some of the interviewed experts stated that they have turned down projects recently in Germany due to capacity bottlenecks (e.g. crane capacity) in their companies or at the subcontractors.

With regard to the transferability of the method to other countries, it is recommended to establish regularly updated market data registers in each country that has wind energy in place and to collect historical data on decommissioning and installations. Moreover, as this study has shown, structured data on pathways beyond the first lifecycle of a wind turbine do not exist, so data were collected by means of expert interviews. Going forward, a data platform allowing the pathways of wind turbines and their components to be traced across multiple lifecycles should be established, e.g. through the introduction of additional data fields in the national market registers. Moreover, this study found that the second lifecycle of the turbines did not take place in the country of their first lifecycle, which also largely applied to a second lifecycle of blades as spare parts. As such, it is recommended that future research broadens the geographical scope and investigates how a tracing system for wind turbines and components could be designed to capture component and material flows across multiple lifecycles and regions. For instance, how might a standardised interface between national market registers be established? In addition, research on the establishment of a digital product pass, e.g. as proposed by the EU (European Commission, 2022), could provide an improved basis for decision-making for different stakeholders along the entire value chain and hence empower them to actively manage their business and supply chain (e.g. stakeholder management, storage dimensioning).

Circular supply chains ought to be designed that aim for a high degree of circularity by applying the entire scope of R-strategies (R3-R9) in a cascading order and extending the overall lifetime of the turbine and its components. The introduced component and material forecast models can be detailed in the future. Dedicated models for the different structural reuse strategies, material-recycling solutions and energy-recovery solutions should be created. These could then be interlinked to reflect the cascading nature of a circular economy and enable adequate capacity planning for each stakeholder. With lessons learned and new technological developments becoming available, stakeholders have to constantly challenge and adapt their strategies to build the most scalable and sustainable circular supply chains. Enhanced cooperation and information-sharing between stakeholders along the entire value chain, coupled with the traceability of the turbines and their components, will support second lifecycle practices and recycling, while policymakers can reduce market entry thresholds. Hence, the development of circular practices for handling decommissioned wind turbines leads to a reduction in the turbines' environmental footprint and reduced dependence on sourcing from single countries when installing new wind turbines, thereby contributing to more sustainable production and consumption patterns (SDG 12) within the wind industry.

CRediT authorship contribution statement

Kathrin Julia Kramer: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Asger Bech Abrahamsen:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Justine Beauson:** Writing – review & editing, Visualization, Conceptualization. **Ulrich Elmer Hansen:** Writing – review & editing, Validation, Methodology, Conceptualization. **Niels-Erik Clausen:** Writing – review & editing, Supervision, Resources, Conceptualization. **Anne P.M. Velenturf:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Matthias Schmidt:** Writing – review & editing, Supervision, Funding acquisition.

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.

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Appendix A. Supplementary data

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