



UK Government

RAF020/2526: Investigation of the potential for lifetime extension, reuse and material recovery for the onshore and offshore wind turbine fleet in the UK

Summary report

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Views expressed in this report are those of the researcher team and not necessarily those of the UK Government.



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Executive summary

Introduction

The UK's transition to a clean energy system will require significant volumes of materials, including steel, concrete, composites and critical raw materials, to build and maintain new infrastructure. This makes supply availability a key risk to meeting legally binding carbon targets. To plan effectively, the UK Government must be able to anticipate and model future sourcing channels for assets, components and materials to meet future demand across the energy system. While research is improving understanding of material needs for the UK's future energy system, gaps remain on the potential for lifetime extension, reuse, and material recovery for the existing energy fleet. In particular, there is limited evidence on the extent to which maintenance and repair activities can extend the operational life of wind energy assets, and on the potential to reuse components and recover materials from wind energy infrastructure at end of life. Addressing these gaps will be important both for supporting the development of the future energy system and for creating new opportunities for UK industry.

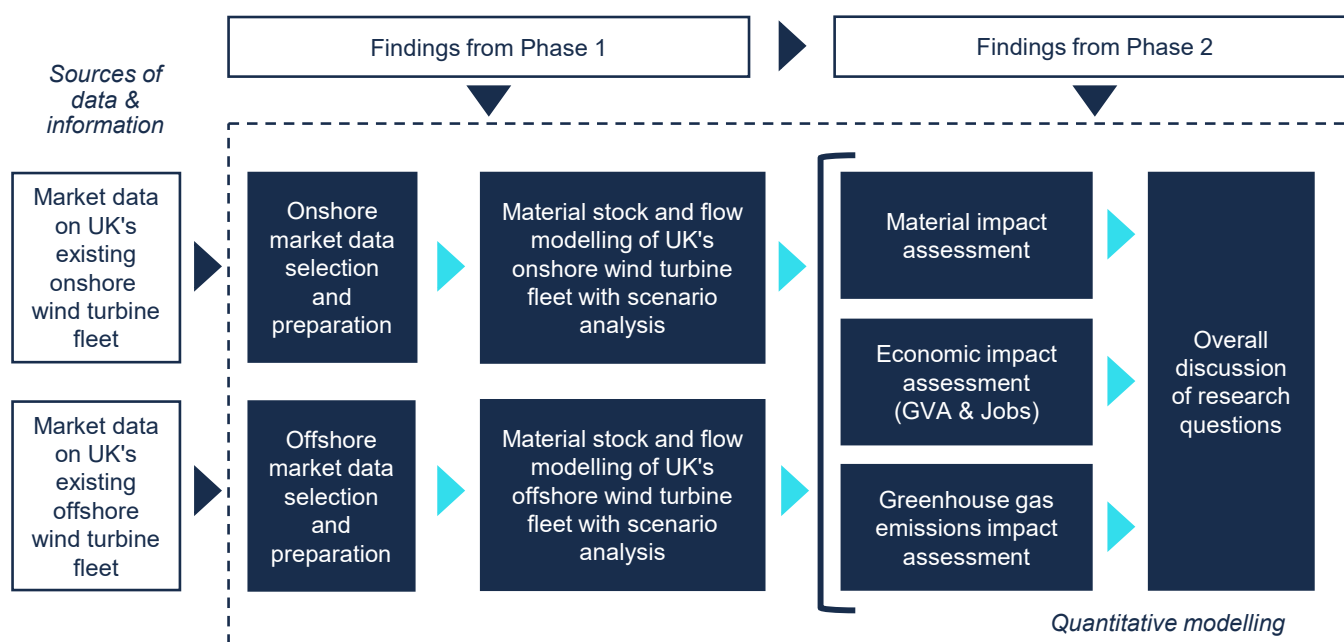
This study therefore investigated the following research objectives:

- Identify to what extent repair and maintenance can help extend the lifetime of existing onshore and offshore wind energy technologies.
- Quantify how much material and reusable components can be recovered from existing onshore and offshore wind assets.
- Identify economic impacts of repair and recovery activities for wind assets.

The study focused on the UK's installed onshore and offshore wind turbine fleet, including foundations, considering key materials including steel, iron, composites, and concrete. The investigation involved three phases of quantitative and qualitative research. The methodology was developed such as to be transferable to other clean technologies (e.g., photovoltaic).

In phase 1, over 4,700 scientific publications were screened for inclusion as part of a literature review, with over 450 included in a final shortlist based on relevance to the research topic. A combination of systematic and narrative reviews provided a baseline of current knowledge to inform the next research phases.

In phase 2, 15 qualitative semi-structured interviews were carried out with key stakeholder groups, including windfarm operators, operations and maintenance (O&M) service providers, and decommissioning and refurbishment companies. Interviews explored current and future practices in the UK wind industry relating to the operation and maintenance of installed wind turbines (e.g. repair and refurbishment) as well as the management of decommissioned wind assets (e.g. reuse and recycling). Interview findings were synthesised to identify key convergences and divergences in each topic area.



Phase 3 involved quantitative modelling informed by the findings of phases 1 and 2. Material flows from the UK's installed wind turbine fleet were estimated to quantify material, emissions, and economic impacts. Scenarios were developed to assess the fleet's potential for lifetime extension, second lifecycle practices, and material recovery of selected components and materials. To capture the full decommissioning and handling quantities for each lifetime scenario, a modelling timeline until 2070 was used.

Key findings

The UK's onshore and offshore wind fleets are already operating in a lifetime extended state.

The findings indicate that both the UK's onshore and offshore wind fleets are already operating in a life-extended state. Under the business-as-usual modelling scenario, approximately 50% of the onshore wind fleet is projected to be decommissioned after 32 years of operation, while offshore wind farms are expected to be decommissioned after approximately 30 years. The qualitative research suggests that these life-extension practices have helped establish existing UK capabilities in the repair and refurbishment of wind assets, creating a foundation for more circular approaches within the sector.

Repair and maintenance are critical enablers of lifetime extension, however, extension is highly variable and dependent on individual site and asset conditions.

While repair and maintenance can enable meaningful lifetime extension, the extent and duration of that extension depend less on turbine age and more on turbine design, spare part availability, data quality, and the wider economic and regulatory context in which assets operate. Decisions are driven more by economic viability and component availability than by age alone. Access to spare parts emerged as a critical enabling factor for lifetime extension.

Stakeholders indicated that the speed and availability of replacement components often outweigh considerations of whether parts are new or refurbished, particularly as turbine models age and original equipment manager (OEM) support diminishes. The enabling conditions for lifetime extension also vary across regulatory and system contexts. For onshore wind, regulatory frameworks for lifetime extension are seen in countries such as Germany and Denmark, whereas the absence of specific UK guidance has resulted in a more case-by-case approach. For offshore wind, additional challenges arise from the separation of ownership between wind farms and transmission assets, creating risks where life extension of generation and grid infrastructure are not immediately aligned.

Data limitations and system-wide constraints currently restrict the potential for repair and maintenance.

The ability to fully assess the impact of repair and maintenances is restricted by limited data availability. Significant gaps remain in areas such as component failure and repair data, inconsistent reporting practices, and the lack of systematic tracking of maintenance interventions across the fleet. These limitations constrain the development of a comprehensive and consistent evidence base to support lifetime extension decision-making, while also limiting the ability of supply chain companies to effectively plan, forecast demand, and scale up repair and refurbishment activities. The findings also highlight the importance of using improved diagnostics and predictive maintenance as key enablers for reliable and optimised asset management. Enhanced monitoring and data availability can help operators better assess component condition, reduce unplanned failures, and support informed decision-making regarding lifetime extension beyond the original design life of wind assets.

Material efficiency improves with longer lifetimes, as both onshore and offshore scenarios show the lowest material demand per energy generated under extended lifetimes.

Most material demand is associated with the initial installation of wind turbines and their foundations. Additional material requirements during the operational phase of the fleet are driven primarily by component replacements, representing a continuing but relatively smaller source of demand. This relationship is particularly important in the context of lifetime extension, where the findings indicate that extending lifetime by 10 years, i.e. from the shorter lifetime to the longer lifetime scenario, results in only marginal increases in total material demands (approximately 1.5%) compared to much larger gains in energy generation (34–40%), indicating clear improvements in material efficiency over the asset lifecycle.

For onshore wind, concrete is the dominant material across all scenarios (9.9 Mt), reflecting the high material intensity of turbine foundations. When considering only component replacements, steel and iron account for more than 80% (0.7 Mt). For offshore wind, total material demand is mainly driven by steel and iron, representing more than 93.5% of the total material demand for all scenarios (10.7 Mt). Even when focusing solely on component replacements, steel and iron remain the primary contributors at 64% (0.7 Mt).

Lifetime extension reduces emissions per unit of energy generated, with modelling showing it consistently delivers the lowest emissions intensity for both onshore and offshore wind.

The emissions modelling shows that extending the lifetime of wind assets reduces overall emissions intensity per unit of electricity generated. For both onshore and offshore wind, longer lifetime results in the lowest emissions per energy generation at 15.65 and 14.92 t CO₂e/GWh, respectively. Although lifetime extension increases material and operational emissions due to additional component replacements compared with shorter-life scenarios, these impacts are outweighed by the significantly higher total energy output achieved over the extended operating period. As a result, net emissions per unit of energy decrease under longer lifetime assumptions. The analysis also highlights that further emissions reductions are dependent on complementary circular economy strategies, with increased component reuse and higher steel and iron recovery rates significantly lowering emissions, reinforcing that lifetime extension is most effective when combined with circular practices.

Waste hierarchy alignment highlights reuse and refurbishment as the highest-value options.

The analysis indicates that where feasible, the highest overall value is achieved by prioritising reuse and refurbishment over recycling, in line with the waste hierarchy. Whole turbine resale and component reuse retain the greatest embedded value, while refurbishment delivers the strongest employment benefits and helps preserve material value within the UK system.

Increasing reuse of components related to key materials, particularly steel and iron (e.g., generators and gearboxes) and composites (blades), reduces emissions intensity across all onshore and offshore scenarios. Steel and iron recovery also contributes significantly to overall emissions reductions per unit of energy generated. From an economic perspective, refurbishment and second-life applications offer the greatest potential for value retention and job creation where technically and commercially viable. However, material recovery remains essential for end-of-life processing, especially for large structural components such as towers and foundations with limited reuse potential. Strengthening UK recycling and material processing capacity, particularly for steel and concrete, is therefore critical to retaining value where refurbishment is not possible.

Economic impacts from both lifetime extension, and repair and recovery activities are positive but highly uncertain.

Considering only repair and recovery activities, the shorter lifetime scenario produces the highest employment impact for both onshore and offshore wind, estimated at 42,000 and 79,500 job-years, respectively. Corresponding estimates for the BAU scenario are 41,000 and 71,000 job-years, decreasing to 37,000 and 69,000 job-years under the longer lifetime scenario. Gross value added (GVA) is broadly comparable across all scenarios. This is driven by turbine and component refurbishment activities, which is the metric with the greatest

variation between scenarios. However, when O&M is also considered, the longer lifetime scenario becomes the most economically beneficial overall for both onshore (504,000 jobs-years and £13.7 billion) and offshore wind (1,330,000 jobs-years and £19.1 billion). This demonstrates that conclusions differ depending on system boundaries, with narrower assessments of end-of-life activity potentially underestimating the wider economic benefits of lifetime extension and ongoing operations.

Economic outcomes are also highly sensitive to key assumptions, particularly refurbishment rates and domestic activity levels. It is therefore recommended that further work is carried out to refine and improve these modelling assumptions.

Domestic supply chain capacity is critical for capturing economic benefits.

Increasing domestic offshore wind decommissioning activity from the current estimated level of 18% to 100% could increase GVA by approximately £5.4 billion, highlighting a significant opportunity for the UK supply chain. Additionally, offshore major component exchange (MCE) activity is currently assumed to have no domestic economic contribution, reflecting the limited UK capacity and reliance on internationally owned assets and vessels for offshore operations. Together, these findings indicate substantial untapped potential across offshore services, much of the value of which is currently generated outside the UK.

Besides a potential for continued scaling of the domestic repair and refurbishment activities, the findings also show that material recovery represents a major opportunity to strengthen circularity and retain economic value within the UK, particularly for high-volume materials such as steel and iron. However, recovery activity for these materials is currently undertaken predominantly outside the UK, highlighting a missed opportunity to establish more domestic closed-loop supply chains. Stakeholders expressed strong interest in retaining high-quality recovered materials within the UK market to support downstream domestic manufacturing across sectors and reduce reliance on imported materials and components.

While lifetime extension can delay decommissioning and material flows, it does not remove future recovery demand, reinforcing the need for long-term workforce, infrastructure, and industrial planning. Growth in domestic recovery and decommissioning capability is currently constrained by high offshore operating costs, logistical complexity, limited recycling and processing infrastructure, and weak business cases for some material streams. Addressing these barriers will require coordinated policy support, investment in ports and processing infrastructure, and the development of UK-based recovery, recycling, and remanufacturing capabilities.

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Glossary

AI	Artificial Intelligence
BAU	Business as usual
CfD	Contracts for Difference
CO ₂	Carbon Dioxide
CO ₂ e	Equivalent Carbon Dioxide
DDPMSG	Direct-Drive Permanent Magnet Synchronous Generator
DDSG	Direct-Drive Synchronous Generator
DESNZ	Department for Energy Security and Net Zero
DFIG	Doubly Fed Induction Generator
DNV	Det Norske Veritas
DOI	Digital Object Identifier
EoL	End of Life
FTE	Full Time Equivalent
GHG	Greenhouse Gas
GVA	Gross Value Added
GW	Gigawatt
GWEC	Global Wind Energy Council
GWP100	Global Warming Potential over 100 years
IEA	International Energy Agency
IEC	International Electrotechnical Commission
iO&M	Intelligent O&M
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency

kW	Kilowatt
LCA	Life Cycle Assessment
LCREE	Low Carbon Renewable Energy Economy
MCE	Major Component Exchange
MRO	Maintenance, Repair and Operations
Mt	Megatonne, million tonnes
MW	Megawatt
µm	Micrometers
O&G	Oil and Gas
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
OFTO	Offshore Transmission Owners
ONS	Office of National Statistics
ORE Catapult	Offshore Renewable Energy Catapult
PM	Preventive Maintenance
REE	Rare Earth Element
REPD	Renewable Energy Planning Database
ROC	Renewable Obligation Certificate
RQ	Research Question
RUK	RenewableUK
RUL	Remaining Useful Lifetime
SCADA	Supervisory Control and Data Acquisition
SME	Small and Medium-sized Enterprise

1. Introduction

1.1 Research background

The transition from the current energy system towards a clean energy system will require high volumes of key materials (e.g. concrete, steel, and composites) to manufacture and develop the required infrastructure and equipment. A successful transition is therefore dependent on the availability and accessibility of materials and components, with insufficient preparation for their provision posing a risk to delivery. Obstacles or delays to building the infrastructure required for the energy transition threaten the UK's ability to meet legally binding carbon budgets. This dependency makes it critical for the Department for Energy Security and Net Zero (DESNZ) to model, anticipate, and pre-empt the material requirements associated with the Clean Power Mission in order to adequately prepare and provision them.

Onshore and offshore wind was chosen for this study as they have been a key aspect of the UK's clean energy transition to date, with large volumes of emission intensive materials, namely steel and concrete, required for the construction of wind energy assets. Assessing the potential for recovering materials from existing wind energy assets is important as strategies to extend the lifetime of energy assets and recovering the components and materials at end-of-life for high value uses can reduce the UK's overall dependence on imports of materials during the clean energy transition.

A circular economy for wind energy turbines and assets can involve durable designs and the longer use of wind farms, turbines and/or components, the decommissioning, disassembly, reuse and recovery of turbines, parts and materials, and recycling, lean manufacturing and waste prevention (complete overview in Velenturf 2026).

1.2 Research aims and objectives

The aims of this project are to:

- Fill a critical evidence gap on the potential for reusing components and recovering materials from onshore and offshore wind assets under diverse lifetime scenarios.
- Develop a replicable methodology for assessing component and material recovery potential in other priority clean energy assets.

The aims will be achieved through addressing the following research objectives and questions:

Table 1. Project's research objectives and questions.

Research objectives	Research Questions (RQ's)
1. Identify to what extent repair and maintenance can help extend the lifetime of existing onshore and offshore wind energy technologies.	a. To what extent can repair and maintenance help extend the lifetime of existing wind turbines?
	b. What is the net impact on material demand associated with extending the lifetime of wind assets?
	c. What is the net impact on emissions associated with extending the lifetime of existing onshore and offshore wind assets?
2. Quantify how much material and reusable components can be recovered from existing onshore and offshore wind assets.	a. How much material and reusable components can be recovered from existing onshore and offshore wind assets?
	b. What is the best (i.e. highest value) use of recovered materials and components?
3. Identify economic impacts of repair & recovery activities for wind assets.	a. What are the potential economic impacts of the repair and recovery activities identified by the research?
	b. What are the respective potential job impacts for repairing and recovering material from existing wind assets?
	c. What is the potential Gross Value Added (GVA) to the economy by repairing and recovering material from existing wind assets?

1.3 Methodology

Methodologies are described in detail in the Appendices, enabling replication of the work and ensuring findings are comparable and relevant. The research comprised of three phases:

1.3.1 Literature Review

Literature review of English language publications from 2015 onwards. Over 4,700 scientific publications (see Appendix A: Literature review methodology) were screened for inclusion (see Appendix A.1 Search and screen methods), with over 450 included in a final shortlist. High priority publications were reviewed first, working down the priority list (see Appendix A.2 Review methods). A small number of publications were selected to be reviewed by two reviewers, ensuring consistency within the methods.

1.3.2 Fieldwork

Qualitative interviews were carried out with key stakeholders working across the materials reuse, repair, and recovery value chain. 15 stakeholders were interviewed in a semi-structured format, broadly following the approach of Kramer et al. (2024), with coding and anonymisation of recorded transcripts undertaken to thematically analyse discussions, to support the quantitative assessment model and scenarios in phase 3.

The interviews were conducted on Microsoft Teams and lasted 45-60 minutes and were carried out with the aid of stakeholder-specific topic guides. The overall method was selected to ground the analytical approach in a pre-existing framework and ensured consistency with the other work phases.

Stakeholder targets were focused on companies either based in, or who have experience of operating in, the UK, although some participants based outside of the UK were included to gain a complete picture of material and component flow from wind farms in the UK. Stakeholder groups interviewed are detailed in Table 2.

Table 2: Stakeholder groups.

Stakeholder group ID	Stakeholder group description	Number of participants
1	UK companies that offer services relating to resale, repair, refurbishment and remanufacturing of wind turbine components	3
2	European companies (trading with the UK) that offer services relating to resale, repair, refurbishment and remanufacturing of wind turbine components	2
3	UK companies that provide services in the installation, operation and maintenance, and decommissioning of wind turbines or wind farms	2
4	European companies that provide services in the installation, operation and maintenance, and decommissioning of wind turbines or wind farms	2
5	Asset owners or developers with on- or offshore wind farms in the UK (particularly those with in-house service teams)	3
6	Waste and resources sector	1
7	Trade bodies, industry groups, certification bodies, and nondepartmental public bodies	1

Stakeholder group ID	Stakeholder group description	Number of participants
8	Academia	0 ¹
9	Original equipment manufacturers (OEMs) that provide services in the installation, operation and maintenance, and decommissioning of wind turbines or wind farms	1
	Total	15

1.3.3 Quantitative Modelling

The quantitative modelling aimed to provide scenarios on material stock and flows from the UK's installed onshore and offshore wind turbine fleet (including foundations) to quantify the impacts on material demand, emission reductions, job creation, and GVA to the UK economy until 2050.

Material stock and flow modelling, economic impact modelling, and emissions impact modelling provided outputs to almost all research questions. The one exception being RQ 1a, which is purely answered by the outputs of phase 1 and phase 2, and functions as input to the material flow modelling.

1.3.3.1 Material Flow Modelling

The developed model enabled the quantification of net material demands for life extension of existing wind turbines (RQ 1b), as well as estimated the recoverable materials and reusable components from existing wind assets (RQ 2a).

The methodology, based on Kramer (2025), was adapted to the UK context and defined scope of this study, incorporating literature and stakeholder insights gathered in the research review. A comprehensive overview of the assumptions taken in the material flow models is provided in Section 3.1 and Appendix B.2 Material flow assumptions.

1.3.3.2 Economic Modelling

The economic model relied on two inputs:

1. The output from the material flow models.
2. Conversion ratios to transform material flow data into GVA or job impact data.

¹ Academic representatives were included in the longlist, however with an extensive literature review already carried out in phase 1, higher weighting was given to direct industry experience.

These ratios were determined using either data from the Office of National Statistics (ONS) or through literature reviews and interviews. More detail on the economic modelling methodology is set out in Appendix C.1 Economic modelling methodology.

1.3.3.3 Emissions Modelling

The emissions modelling assessed the net impact that life extension has on the emissions produced by onshore and offshore wind assets using a Life Cycle Assessment (LCA). The LCA utilised relevant material and activity data, assigned appropriate environmental factors, collated the flows of material and energy from the system and reported the environmental impacts. It was critical that the LCA complied with standardised methodologies used internationally for reporting environmental impacts. The process is governed by the following standards and were applied to the emissions modelling:

- ISO 14040 - Principles and framework
- ISO 14044 - Requirements and guidelines
- GHG Protocol - Product Life Cycle Accounting and Reporting Standard

More detail on the emissions modelling methodology is set out in Section 3.1.4.

2 Research Review

Findings from the literature review and stakeholder interviews highlight the current state of knowledge, identifying gaps, and summarising data availability for topics directly relevant to the development of the quantitative model.

2.1 RQ 1a: Potential for repair and maintenance to support lifetime extension

An overview of current lifetime extension strategies, as well as repair and maintenance technologies, are discussed, based on insights from interviews and 40 reviewed publications. More insights were provided for onshore wind than offshore wind, reflecting an older and more extensively studied onshore asset base.

Key themes emerging from the literature included lifetime extension decision making (Ziegler et al., 2018; Nejad et al., 2022) with aspects such as:

- Legal requirements (Ziegler et al., 2018)
- Safety and standards/guidance such as for risk assessments for building safety (Ziegler et al., 2018)
- Cost considerations including financial risks related to turbine blades (Jacobs, 2025) lifetime extension and material consumption (Liu et al., 2022), and intelligent Operations and Maintenance (iO&M) costs (Peng et al., 2023)
- Turbine conditions including structural models, site conditions and data availability (Ziegler et al., 2018)
- Operational history such as environmental conditions and maintenance (Jacobs, 2025)
- Policy, market and environmental conditions (Ziegler et al., 2018; Jacobs, 2025)
- Market size and economic benefits (BVG Associates, 2023)

The literature also discussed lifetime extension concerns and gaps across technical, economic, legal, skills and social acceptance domains (Ziegler et al., 2018) as well as availability of refurbished components for lifetime extension projects (Jacobs, 2025).

Findings from the stakeholder interviews align with the literature, consistently identifying access to spare parts and the financial viability of continued operations (including revenue from subsidies and cost of O&M) as the most important variables. The most common secondary considerations raised were network capacity and the duration of land ownership or leases. Many respondents also raised points about the overarching policy environment and its impact on decision-making, such as:

-
- export capacity restrictions and uncertainty on connections reform that has delayed decisions towards repowering and inadvertently incentivised life extension;
 - the Offshore Transmission Owners (OFTO) and operators divided responsibility for assets creating uncertainty around decision making for offshore wind;
 - the end of the Renewable Obligation Certificates (ROC) scheme, leading to reduced financial certainty;
 - planning frameworks in relation to repowering consenting and permitting approvals

2.1.1 Average lifetimes, assumptions and trends for lifetime extension periods

A key consideration in lifetime extension is defining the normal design lifetime and the point at which life extension begins. According to International Electrotechnical Commission (IEC) standards, normal design lifetimes are at least 20 years (Ziegler et al., 2018). However, both the literature and stakeholder interviews indicate that actual operational lifetimes frequently exceed this baseline, introducing variability and uncertainty into forecasting.

Across the literature, assumptions regarding design lifetimes are relatively consistent, typically ranging from 20 to 25 years for both onshore and offshore (Heidak et al. (2025; Hou et al., 2017; WindEurope, 2020; Meng et al., 2025; Stravens, 2025). However, upper and lower limits around this average lifespan can vary significantly, Meng et al. (2025) consider lifespans ranging from 15-35 years while Stravens (2025) explores a potential for lifetime extension in offshore wind of 30-40 years.

These findings are broadly aligned with stakeholder interviews. Participants were unanimous that life extension is planned for in the UK, and already happening, for most onshore assets. Most responses cited extensions of 5-10 years on the original design life of 20-25 years for onshore turbines as common practice, with examples given of operational assets already operating at 30+ years. In general, interviewees were unable to estimate a maximum achievable lifetime for assets currently in operation, but one onshore site was cited where the wind farm is planned to run for as long as 38 years.

Practical applications were found to differ by region. Stravens (2025) notes that in Germany, offshore lifetime extensions are typically limited to a maximum of 10 years, whereas in neighbouring Denmark, recent permits have allowed extensions of 10–25 years. This illustrates both the variability in assumptions used in the literature and the influence of regulatory frameworks on lifetime extension practices.

In the UK, BVG Associates (2023) assume a design life of 25 years with the expectation that 50% of turbines undergo a further 5-year life extension. However, this assumption may not reflect current market trends. For instance, Jacobs (2025) reported from stakeholder interviews that wind farm operators sometimes repower turbines after 10–15 years of operation, while in Scotland, the market trend is to extend turbine lifetimes by up to 10 years beyond the design life. A total operational life of 30–35 years is also consistent with observations reported by Hou et al. (2017) in Sweden.

Both literature and interviews emphasise that lifetime is not a fixed parameter but is increasingly being treated as a variable. Some studies no longer define a single expected lifetime for wind assets, such as Lichtenegger et al. (2020) modelling a stochastic lifetime for turbine blades reflecting substantial variation in component durability. More broadly, the lifetime of wind turbine components may vary substantially (see also section 2.1.2.1). Kasner (2022) suggests that substantial lifetime extension, potentially up to a doubling of service life, is feasible for Vestas V90 foundations and towers, provided that nacelles and rotors are replaced after 25 years, and Hou et al., 2017 suggests foundations may last over 100 years.

Repowering can further extend the effective use of wind farm assets and components (Hou et al., 2017). Opportunities include partial repowering, in which nacelles and rotors are replaced while towers and foundations are reinforced, typically extending the operational lifetime of a wind farm by approximately ten years. While repowering continues to face constraints, life extension is expected to become less common as repowering increases (WindEurope, 2020). In the US, financial incentives have reportedly driven repowering operations within the first ten years of wind farm lifetimes (Meng et al., 2025) as companies seek to maximise income and power production with newer, bigger assets, rather than extend operational lifetimes.

Whilst some of these studies have provided insights into offshore wind, the evidence base is generally more limited, reflecting the relatively young asset base. Early offshore turbines were designed for 20 years, although stakeholders anticipated operational lifetimes of 25–30 years. Newer assets are also increasingly being designed for 25 years, with one interviewee noting examples of developers factoring 5-10 years life extension into the design phase of newer offshore wind assets.

There was divergence about what life extension may be possible in the future. Many interview participants believed that longer periods of life extension in the future would be enabled by more proactive maintenance strategies, improvements in technologies such as condition monitoring, and the growth of the spare parts and refurbishment supply chains.

However, some responses highlighted that more refined design of new turbines lessened the potential for life extension in the future. These stakeholders said that newer onshore and offshore wind sites are being engineered for a pre-planned longer operating life, enabled by turbines tailored to site conditions and incorporating design improvements learned from previous generations. In contrast, first generation turbines were manufactured with a bigger safety factor and shorter planned design lives to account for the uncertainties in operating conditions (especially for offshore) and therefore are now better candidates for life extension beyond what was originally planned.

“I think the life would be a lot more finely tuned for the newer turbines, so everything would come to a natural end more or less at the same time if the designs are... as tuned as we would hope they would be with the newest ones.”
OEM O&M company

2.1.1.1 Lifetime extension decision making

Decisions about onshore and offshore wind energy infrastructure lifetime extensions can be influenced by a range of technical, economic, environmental and governance aspects, along with stakeholder requirements (Ziegler et al., 2018; Velenturf, 2021; Nejad et al., 2022). Robust assessment of these factors requires comprehensive and asset-specific data; however, empirical evidence remains limited (Lund and Madsen, 2024). As a result, larger operators are typically better positioned to undertake lifetime extension decisions, owing to access to broader datasets across their asset portfolios, which can be used to inform and calibrate decision-making models.

2.1.1.1.1 Legal requirements and standards

Ziegler et al. (2018) analysed the state-of-the-art practices for onshore wind lifetime extension in Germany, Denmark, and the UK. They found that Germany and Denmark have established consistent technical assessment processes for lifetime extension that are embedded within legal and regulatory requirements. In Germany, these practices involve both analytical and practical assessment undertaken by qualified experts, including structural safety checks conducted in accordance with specific standards for construction technology and wind turbine lifetime extension (DNVGL, 2016). In Denmark, wind farm operators are required to commission inspections from certified companies covering key structural components, such as foundations, towers, frames, yaw bearings, and bolt tightening, on an annual basis, alongside visual blade inspections every three years.

In contrast, the UK lacks specific guidance governing lifetime extension, beyond general industrial safety regulations that apply irrespective of wind farm age. This gap is also reflected in stakeholder interviews, where several respondents highlighted the absence of clear standards as a barrier to long-term planning and investment. Some stakeholders noted that this uncertainty may lead asset owners to adopt more conservative approaches, including earlier decommissioning or repowering.

“I think the thing that we need to get is clear guidance on what the owner/operators need to do. So whether that's a technical spec, whether that's a standard, whatever that may look like, that needs to be introduced very quickly to give the owner/operators and investors a clear “this is what we need to set aside for these machines” and they need to start looking at this in year 15, if not before.” UK refurbishment company

Safety considerations are central to lifetime extension decision-making and are commonly addressed through structured risk assessments (Ziegler et al., 2018). Design lifetimes are nominally 20 years (based on IEC standards), meaning that wind turbines are designed to withstand operational and environmental loading for that period of time while maintaining sufficient structural safety. Safety level assessments are based on calculating the annual probability of structural failure. This calculation is based on assessments of the ultimate and fatigue strength against loading and safety factors. In cases where the site conditions during the turbine lifetime have been less harsh than anticipated, standards bodies such as Det

Norske Veritas (DNV) may consider it unnecessary to reassess ultimate limits and the assessment focuses on fatigue limits only (Ziegler et al., 2018).

Lifetime extension assessments differentiate between load-bearing and non-load-bearing components, both of which play an important role (Ziegler et al., 2018). For load bearing components, the Remaining Useful Lifetime (RUL) is estimated, covering the time during which structural reserves are enough to maintain a sufficient safety level as a prerequisite for lifetime extension (Nejad et al., 2022). The RUL is determined by the structural component with the lowest remaining life, and as such replacing such critical components can increase the lifetime of a whole turbine (Ziegler et al., 2018; Nejad et al., 2022). While non-load-bearing components are less critical to structural integrity, their failure can still result in turbine downtime, production losses, and increased O&M costs (Ziegler et al., 2018).

Beyond technical considerations raised in the literature, stakeholder interviews identified a range of non-technical constraints influencing life extension decisions. Land ownership and leases were described as complicating factors in an onshore life extension decision, and in several cases were cited as limiting the lifetime of projects.

“I would say that there are some barriers in terms of land leasing and agreements. I've spoken to a couple of people who've had their lease expire and not renewed, so that's stopped them life extending.” Waste and resources company

In contrast, for offshore wind farms, seabed leases were cited as part of the many aspects of a lifetime extension decision, but the relatively long leases awarded do not appear to constrain project lifetimes.

Network capacity was also raised as an issue particularly influencing onshore wind asset life. If local grid capacity is limited and repowering is not deemed viable, then life extension is considered the default alternative. One response on this topic expanded further to speak about the Clean Power 2030 connections reform process. This has put a cap on new network capacity in Scotland for onshore wind out to 2035, and thus it was felt would largely favour life extension over repowering (where sites would install additional generating capacity).

For offshore, the main point of discussion around grid focussed on ownership of the transmission asset. This is held by an OFTO and is separate from the wind farm. There is a risk that assets may be stranded if the life extension of both pieces of infrastructure is not carried out in parallel.

Both the literature and stakeholder evidence highlight that, while technical assessment methodologies for lifetime extension are relatively well established in some EU markets, the UK context remains less clearly defined. This lack of standardisation introduces uncertainty into decision-making and may influence the balance between lifetime extension, repowering, and decommissioning strategies.

2.1.1.1.2 Cost considerations for life extension

Extending the operational lifetime of wind turbines can increase returns on investment and reduce average lifetime costs at the wind-farm level. However, these potential benefits may be partially or fully offset by increased operations, maintenance, and repair costs as assets age. Maintenance activity is expected to increase in frequency with longer operational lifetimes (Stravens, 2025), although empirical evidence quantifying this effect remains limited.

Existing studies generally indicate that lifetime extension can be economically favourable under certain conditions. A study by Jacobs (2025) examining onshore wind decommissioning in Scotland found that, when assessed at the level of the full turbine, lifetime extension represents the optimal end-of-use strategy, with refurbishment for reuse at a different location ranking as the second-best option.

However, cost dynamics are highly sensitive to asset condition and repair requirements. Liu et al. (2022) discuss costs of lifetime extension focused on blades and composites end of use processing options for two onshore wind farms in China. The study shows that defect rates and associated repair costs are key factors influencing lifetime extension decisions, including additional material consumption. Repairs were grouped into minor repairs, caused by minor environmental events, and intermediate/major repairs, usually caused by design defects and aging. Intermediate/major defects require more material and time for repairs. In 2015, material use was 1,089 kg per year for repairs across the two wind farms, i.e. 545 kg/year for a 50 megawatt (MW) onshore wind farm with 66 turbines.

These findings are strongly reflected in stakeholder interviews, which consistently identified the balance between revenue and the cost of continued operation as the primary determinant of lifetime extension decisions. Operating costs include general scheduled maintenance (e.g. oil changes), obtaining and replacing components (either for a failure or planned replacement), and rectifying structural issues with, or damage to, the asset (e.g. repairing cracked blades). Responses indicated operating costs were fairly well constrained for aging onshore assets, but was cited as a major uncertainty for similarly old offshore projects.

Stakeholders emphasised that, beyond technical feasibility, lifetime extension ultimately becomes a commercial decision as assets age, with operators weighing the cost of repair against the value of continued operation. In some cases, life extension may be used as a short-term strategy to defer decommissioning costs, particularly where these have not been fully provisioned.

“Once they're getting towards the end of life, it becomes a commercial zone. Then are you going to pay the cost to repair or just be done with it?” EU O&M company

Revenue stability was also identified as a critical factor. Wind farm revenue is commonly linked to support regimes such as subsidies (e.g. Feed in Tariff, Renewables Obligation) or price stabilisation mechanisms (e.g. Contract for Difference, Power Purchase Agreement). The term of these financial instruments was considered one of the key determinants of the wind farm's operational life. The expiry of the Renewables Obligation in 2027 (for early scheme

participants) was particularly mentioned as a tipping point for some onshore assets, with wind farms being life extended to this date and then planned to be decommissioned or repowered when the subsidy is no longer applicable.

International comparisons further illustrate the importance of policy design. France was a commonly cited example of a contrasting subsidy regime to the UK, where repowering is incentivised over life extension by shorter, time-limited subsidies, and there is a growing decommissioning and turbine resale market.

The evidence indicates that while lifetime extension can offer economic benefits, its viability is highly context-dependent, shaped by the interaction between maintenance costs, asset condition, and revenue frameworks.

2.1.1.1.3 Assessing turbine condition

Turbine condition is a key factor influencing lifetime extension decisions and is shaped by operational history, including site conditions and maintenance records (Ziegler et al., 2018; Jacobs, 2025). Operational history can provide insight into whether turbines have been exposed to harsher environmental conditions than anticipated, potentially reducing the feasibility of lifetime extension (Jacobs, 2025). Conversely, earlier generations of turbines were in some cases overdesigned, increasing the likelihood of residual structural reserves that support extended operation.

Improved O&M strategies through condition monitoring and predictive/preventative maintenance would optimise turbine health and reduce loads on turbine components during operation (Ziegler et al., 2018). This was also recognised by Jacobs (2025), arguing that maintenance efforts by asset owners in Scotland is “significantly variable”. Methods for structural health monitoring and fatigue assessments are extensively researched (Velenturf, 2021). Nevertheless, decision-making in practice remains constrained by data availability and quality.

Site condition data are typically combined with structural models to assess the safety of operating turbines beyond their designed lifetime. However, such assessments may be limited by insufficient data to adequately calibrate these models (Ziegler et al., 2018). In practice, the collection of high-quality site and operational data can be costly and technically challenging, leading to the use of analytical or surrogate models that may provide less reliable estimates of structural safety (Ziegler et al., 2018). Standardised procedures to collect and share data on wind turbines’ operational history, site conditions and, if possible, design data would help in resolving this issue.

Newer turbine generations are more likely to incorporate advanced monitoring systems, improving data availability, with additional information increasingly obtainable through Supervisory Control and Data Acquisition (SCADA) systems. At the same time, newer turbines may have been designed more precisely for a defined service life, increasing the need for robust assessment techniques to estimate remaining life. Ongoing limitations in data sharing, particularly relating to proprietary turbine design information held by OEMs, continue to constrain the effectiveness of lifetime extension assessment models.

These findings are reflected in stakeholder interviews which emphasise that lifetime extension decisions are highly site-specific and fundamentally data-driven. Respondents indicated that formal assessment processes typically begin at 17–20 years of operation for onshore wind farms, and slightly earlier (approximately 15–17 years) for offshore assets, reflecting both the importance of early data collection and the greater uncertainty associated with offshore operating conditions and the long timelines required for planning end-of-life decisions.

2.1.1.1.4 Policy and market conditions

Ziegler et al. (2018) discuss the role of subsidy considerations in influencing lifetime extension decisions for onshore wind in the UK. Historically, wind farms under 5 MW received fixed feed-in tariffs, with rates guaranteed for 20 years, though decreasing since 2012. While wind farms over 5 MW were supported through the Renewable Obligation, introduced in 2002 and closed to new entrants in 2016, with a grace period extending to 2019. Since the withdrawal of these support mechanisms, the policy landscape has shifted. In the absence of government subsidies, wind farms are increasingly exposed to electricity market volatility, alongside heightened financial risk associated with O&M costs and turbine downtime (Ziegler et al., 2018).

Both the literature and stakeholder interviews indicate that this transition has made the business case for lifetime extension more uncertain. While repowering may offer an alternative, it is often constrained by planning requirements, social acceptance, and grid availability (WindEurope, 2025). In contrast, interview responses indicated that UK onshore wind policy and devolved planning frameworks are generally supportive of life extension, and that it is relatively straightforward in most cases to obtain extensions to consent durations.

For offshore wind, the policy environment was talked about with uncertainty, with life extension not clearly defined in policy or tested in practice, although consensus on this issue between devolved nations was emphasized as being important. For offshore assets, where decommissioning is seen as costly and risky, and repowering of early sites is unlikely, there is a view that life extension should be considered to enable these assets to fully contribute towards UK energy security.

“There is the big opportunity for lifetime extension and energy security because the assets are already in the water, especially with regards to offshore where we don't know how to fully decommission infrastructure. So thinking about it from an energy security point of view, we want to make sure there are routes to facilitate lifetime extension.” Trade body

“For the turbines that are ageing now and unless we catch it soon, then there's going to be quite a few that are decommissioned with quite a lot of life left in them. That's the shame of it and certainly from the turbine point of view we're finding that the bit above the water line that we're responsible for usually actually has generally a lot of life left in it.” OEM O&M company

A further market consideration pertains to availability of wind turbine parts (BVG Associates, 2023). Lifetime extension is reliant on access to components which may no longer be

manufactured by OEMs and are only available through second-hand markets (Jacobs, 2025). A strong consensus emerged through the stakeholder interviews that the ability to life extend critically depends on access to spare parts. As turbines get older, it is common that the OEM and its suppliers no longer manufacture the same volume of components, or indeed, may move away from the turbine model entirely. This not only decreases availability, it increases costs from lost production; increases lead times for replacements and often increases the cost of obtaining spares.

Interviewees were also unanimous that, where asset owners were open to the use of refurbished parts, the speed and availability of parts is the primary factor that dictates whether a refurbished or new component is used for either a scheduled replacement or failure.

“Speaking...to a technician and they need a part yesterday they will take whatever part is available. Whether it's new, whether repaired. From that side, from an engineering side that's quite critical. You're talking about an asset and... if it's not running then it's important.” UK O&M company

It was noted there can be tension between some OEMs and independent O&M companies, with the former not wanting to supply spares outside of their own service agreements. This can lead to refurbished components being preferred by independent service providers. However, one offshore asset owner noted that they may choose to use OEM parts for more expensive components, due to the extended warranties, especially for major components that impact on the whole turbine's operation.

Both policy and market factors play a central role in shaping lifetime extension decisions. While supportive planning frameworks may enable extension in principle, the absence of long-term policy clarity, combined with revenue uncertainty and supply chain constraints, can limit its practical viability.

2.1.1.2 Lifetime extension decision making approach

Bringing decision making aspects together, Tartt et al. (2021) reviewed learnings from other industries to apply to wind. They propose a lifetime extension assessment method based on seven summary learning points. The framework highlights that assessment methods vary depending on data availability, ranging from simplified approaches where design documentation is limited, to deterministic or probabilistic methods where more detailed information is available. However, across all approaches, practical elements such as visual inspection of critical components and site-specific evaluation remain essential, reinforcing that lifetime extension assessments are inherently site-dependent.

The proposed process begins with systematic data collection, followed by the selection of an appropriate analytical approach, typically combining modelling and simulation with physical inspections, before determining the feasibility and duration of lifetime extension. Complementary methods, including condition monitoring, drone-based inspections, and advanced sensing techniques, further support assessment by improving detection of structural degradation and informing estimates of remaining useful life (Oh et al., 2024). Data inputs are

drawn from a wide range of sources, including SCADA systems, maintenance records, design documentation, and operational history, with increasing use of AI to support data processing and predictive analysis.

This approach is supported by the evidence gathered on industrial practice, where data on the condition of the turbine is also used in life extension decision making. This may take the form of physical inspections, digital twin modelling, and services on the rotating components.

“In the life cycle or life extension assessment, if we find there to be structural fatigue, or degradation within the blades, the tower, the foundations, this is obviously a red flag...where we see a project as potentially not being a good candidate to extend.” Onshore asset owner

Detailed work may only be carried out on a small number of the most exposed turbines within the array and then extrapolated to other areas of the wind farm. Some interviewees also stated this approach may be extended even further and applied to other turbines of the same model within the asset owner’s fleet, at different sites.

Overall, this underscores that reliable lifetime extension decisions depend on the availability and quality of data, as well as the integration of analytical and practical assessment methods. While such approaches provide a structured basis for decision-making, their effectiveness remains constrained by data limitations and variability across assets.

Stakeholder evidence reflects these limitations in practice. Interviewees were consistently unable to quantify the proportion of their own operating fleet, or the wider UK fleet, that will eventually undergo life extension, however, indications were given that a very high proportion of assets would be under consideration.

“It’s fair to say that the assessments we’ve done haven’t identified anything that couldn’t go into life extension.” Onshore asset owner

2.1.1.3 Lifetime extension concerns and evidence gaps

A range of persistent concerns and evidence gaps are identified relating to wind turbine lifetime extension across technical, economic, legal, and social domains (Hou et al., 2017; Ziegler et al., 2018; Jacobs, 2025). These issues are reported across several European countries, including Denmark, Germany, and the UK, with market-related challenges also highlighted in Sweden. Technical barriers primarily relate to incomplete or inaccessible documentation, including gaps in operational and wind history data, original design information, and uncertainty surrounding changes in wind resources due to environmental change or the proximity of neighbouring wind farms (Ziegler et al., 2018).

Economic concerns centre on exposure to electricity market conditions, policy uncertainty, and the availability and cost of spare parts (Hou et al., 2017; Ziegler et al., 2018; Jacobs, 2025). Illustratively, Hou et al. (2017) report the decommissioning of an offshore wind farm in Sweden after just 15 years of operation, driven by difficulties in sourcing spare parts alongside high repair and upgrade costs. Legal and institutional challenges include limited regulatory clarity

around lifetime extension, as well as constraints related to land access and grid infrastructure (Ziegler et al., 2018). In addition, social factors such as shortages of skilled maintenance personnel and reputational risks associated with turbine failures further influence lifetime extension decisions (Ziegler et al., 2018).

2.1.2 Repair, replacement and refurbishment

Section 2.1.1, indicated that lifetime extension is likely to be associated with increased maintenance and repair activity. Building on this, the following section reviews the current knowledge base on repair rates and technologies.

2.1.2.1 Failure, replacement and refurbishment rates

Several publications discussed wind turbine failure mechanisms, failure rates, and associated repair, replacement, and refurbishment frequencies (Schreiber et al., 2019; Mishnaevsky, 2021; Peng et al., 2023). Failure rates reported in the literature encompass a range of events, including minor repairs, major repairs, and major component replacements (Oh et al., 2024). For example, Oh et al. (2024) estimate that an average offshore wind turbine experiences approximately 8.3 failure-related events per year, comprising around 6.2 minor repairs, 1.1 major repairs, 0.43 major replacements, and 0.7 failure events.

Despite the breadth of literature, data on failure and replacement rates remain fragmented and difficult to access, often due to commercial confidentiality (Schreiber et al., 2019). This closely aligned with the findings from the stakeholder interviews, where interviewees could not quantify failures or replacement rates for any components, although there were some general comments about major component failures increasing as the turbine aged. Instead, many responses commented on the lack of available data on replacement or failure rates, with some expressing doubt as to whether this was ever routinely captured. Others pointed to commercial sensitivities as barriers to getting access to this information, particularly for OEM parts. In instances where this data was recorded, it is held by specialist roles or teams within the organisation, and not widely shared or known outside of these individuals. Supply chain companies dealing with components can sometimes indirectly infer failure rates through demand for certain parts.

While this review confirms substantial variability and uncertainty in reported rates, the literature nonetheless provides comparatively robust insights into common damage mechanisms and failure modes across turbine components. Peng et al. (2023) provide a comprehensive review of component failure mechanisms across both onshore and offshore wind, finding that the most prevalent failures occur in blades and gearboxes, for which relatively extensive evidence is available. By contrast, failures in pitch and yaw systems appear less well documented.

For blades, evidence suggests that damage mechanisms vary over the blade lifecycle, with manufacturing defects and surface damage dominating early years of operation, followed by lightning-related damage and structural cracking at later stages. Notably, studies indicate that a substantial proportion of blade issues occur within the first five years of operation (Mishnaevsky et al., 2022). Given the mechanical stresses experienced by turbine blades and

the observed failures rates, it appears unrealistic to assume that turbine blades are replaced once every 20 years as suggested by (Zhuo et al., 2023). This assumption would imply a 0% replacement rate during the designed lifetime. By contrast, Li et al. (2021) estimate that one blade per turbine was replaced over its 20-year lifetime, corresponding to a replacement rate of 33%. Schreiber et al. (2019) derive replacement rates of 0.024 units/year for rotor and 0.005 units/year for blades, based on pre- 2007 data, and assume improvement rates to reach an updated figure. However, the reliability of such estimates is limited, particularly given the reliance on older datasets and assumed performance improvements, a limitation also acknowledged by the authors. During the stakeholder interviews, blades and blade bearings were highlighted as an area of concern for aging turbines, with failures mitigated against by regular inspections via drones or physical surveys, and in-situ repairs.

More generally, Tota-Maharaj and McMahon (2021) assume a 20-year lifetime for turbines, with part replacements 10 years after commissioning. They draw upon older data sources by Andersen for average annual replacement rates of 3.1% for gearboxes, 2.9% for generators and 2.2% for each blade. Electrical systems account for the highest failure rate in wind turbines, but gearbox failures account for the highest amount of downtime of any single component (Peng et al., 2023). Most wind turbine gearbox failures (76.2%) are caused by bearing problems. Nejad et al. (2022) explain that main bearings experience repeating, large-scale fluctuations in load and suffer failure rates of up to 30% during a 20-year design life.

Gears were the second leading cause of failures (17.3%) (Peng et al., 2023). Sathyan (2023) argue, similarly, that gearboxes in drivetrain systems tend to be sensitive to damage and may cause 2-3 times more downtime than other component failures. Arguably, only 10% of bearings will function without issues throughout their lifetime, but 90% will fail due to insufficient lubrication (30%), installation fails (40%) and manufacturing defects (20%). Peng et al. (2023) point towards tooth surface corrosion, wear, gluing and breaking teeth as key failure issues (rooted in poor maintenance and environmental causes) which, depending on interpretation, is likely aligned with the dominant reason for failure i.e. bearing faults driving more the 50-70% of failures (Sathyan, 2023; Zhao et al., 2024).

Drivetrain replacement rates are challenging to gauge. The reviewed literature indicated that most turbines require significant gearbox repairs and/or replacements approximately 5–7 years into their designed 20-year lifetime. Bearing failures are a major contributor to drivetrain downtime. They account for around 70% of gearbox downtime and between 21% and 70% of generator downtime, depending on turbine size: approximately 21% for small turbines (<1 MW), 70% for medium turbines (1–2 MW), and around 50% for large turbines (>2 MW). The lower share for larger turbines may be partly explained by the increasing use of permanent-magnet generators, which are associated with lower failure rates (see Carroll et al., 2014). This observation was also noted during the stakeholder interviews, where direct drive turbines were identified as being easier to maintain, due to not having a main gearbox as a point of maintenance or failure.

Among gearbox and generator failures, Schreiber et al. (2019) estimates around 60% and 10%, respectively require replacement, however this is based on older datasets. Zhuo et al.

(2023) report higher replacement rates, estimating that 95% of gearbox failures and 19% of generator failures in doubly fed induction generator (DFIG) turbines lead to replacement. By contrast, replacement rates for direct-drive generators are estimated at around 24% (Zhuo et al., 2023). Li et al. (2021) assume a uniform replacement rate of 15% for generator components, which, in light of the variation reported in the literature, may underestimate replacement needs for some components. Many of these estimates rely on older datasets or simplified assumptions. Although more recent turbine designs may exhibit improved reliability and therefore lower replacement requirements (Nejad et al., 2022), the available evidence remains limited. Consequently, it remains difficult to draw robust conclusions on drivetrain replacement rates without more recent empirical data.

Zavvar et al. (2025) report a failure ratio rate of 0.938 for pitch systems (the ratios highlight the relative performance and reliability, with values closer to 1 indicating higher downtime or failure rates), indicating frequent issues. Common failures to the pitch system include issues with the pitch shaft cabinet battery under voltage, abnormal hub detection data i.e. communication issues and the paddle angle deviation exceeding the limit (Peng et al., 2023).

The yaw system may produce abnormal noise due to a number of issues, namely deterioration of driving motor oil, transmission bearing damage, broken ring tooth, uneven ring clearance, lack of grease in yaw system and brake damping pressure exceeding the limit. Further issues relate to the yaw drive machinery getting stuck and inaccurate yaw positioning relating to a failing brake (Peng et al., 2023).

In addition to repair and replacement rates, BVG Associates (2023) estimate refurbishment potential for ten wind turbine components. These components were selected based on their suitability for remanufacturing, material recovery, and technological feasibility. The assumed refurbishment rates are derived from operational experience, desk-based research, and extrapolation. For several components, replacements are assumed to occur primarily during years 11–15 of operation, with a substantial share considered repairable. For example, callipers are assumed to be replaced at rates of 10% offshore and 100% onshore during this period, with around 80% considered repairable. Converter phase modules are estimated to have replacement rates of 8–24% offshore and around 8% onshore, all of which are assumed to be repairable. Gearboxes and generators show comparatively low replacement rates (1–2% and 1–4%, respectively), with 80–95% and around 95% of these components considered repairable. Other components such as hydraulic stations (20%), drive shaft assemblies (1–2%), transformers (2%), three-phase motors (5%), and yaw gears (10%) are also assumed to be largely repairable. Slip rings are assumed to be fully replaced during years 11–15, with approximately 60% considered repairable. Despite this technical potential the recertification of wind turbine components and parts is not yet common practice, which may constrain wider market adoption (Ramos et al., 2023). For high-risk components such as wind turbine blades, refurbishment and reuse may be particularly challenging due to safety and certification requirements (Jacobs, 2025).

Finally, while less prone to failures, failing turbine structures are associated with high downtime, indicating that structural failures cause significant delays in turbine operation (Zavvar et al., 2025).

2.1.2.2 Maintenance strategies

O&M strategies play a central role in determining the feasibility, timing, and cost of wind life extension. The literature on maintenance optimisation is primarily focused on offshore wind, owing to the higher costs and logistical complexity associated with O&M activities. Maintenance strategies may operate at whole turbine or component levels and span a wide range of approaches including corrective maintenance, routine inspections, preventive maintenance (calendar, age, or use-based), reliability-centred and condition-based maintenance, risk-based maintenance, and opportunistic replacement (Shafiee et al. 2019; Oh et al., 2024).

The findings of the study are supported by the stakeholder interviews, where wind turbines were described as being generally under OEM service packages for the first 5-15 years of operation. After this time, the asset owner may choose to move away from the OEM service and this opens the market up to independent service providers, who therefore typically work and specialise on mid-life and aging turbines. These companies report being asked to explore opportunities in refurbished components and alternative maintenance strategies, with cost saving and longevity of operation key priorities for asset owners. Maintenance planning must also account for different failure types. Minor failures can often be detected remotely and repaired quickly, whereas major failures may require extensive repairs or component replacement and specialised vessels.

Respondents explained that major components (gearbox, generator, main shaft) are either replaced due to age-related “wear and tear” or failures. Unexpected major component failures represent a big cost for the operator, with crane costs, personnel, and turbine downtime. A failure on one asset is often repeated on others of the same specification and age, so gives a window for preventative or proactive maintenance and cost-saving interventions.

“If I was to characterise the wind industry generally, it's a very reactive tactical market compared to other industries. So, what I mean by that is people will talk about running to on condition which is a fancy way of saying run to failure, which is challenging. Because often you get very little notice before that failure occurs, and then suddenly everyone is racing to respond.” UK refurbishment company

Despite the wide range of available approaches, identifying the most cost-effective maintenance strategy remains challenging. Comprehensive approaches such as risk-based maintenance can incorporate reliability, failure detection, and cost factors, but are often computationally demanding compared with classical replacement policies. As a result, there is a need for practical methodologies that combine classical maintenance approaches with structural reliability analysis to support maintenance decision-making in large-scale offshore wind farms.

During the stakeholder interviews, several companies carrying out refurbishment work across different industries reported that the onshore wind industry is still perceived as “reactive”, that assets are run to failure, and that asset owners are extending the life with no additional investment in the turbines. They highlight missed opportunities for longer successful operations that would be possible with proactive refurbishment of major components, as is common practice in other industries such as oil and gas (O&G), and pharmaceuticals.

In contrast, responses relating to offshore wind maintenance indicate the higher costs of repairs and maintenance are driving more predictive and proactive strategies. Increasingly, use of asset monitoring data is allowing operators to specifically target life extension. A large part of this is identifying issues before they occur and attempting to estimate the remaining useful life of components. Multiple responses highlighted the importance of early consideration of life extension and that waiting until the asset reaches its design life is deemed too late to effectively manage its condition.

“So if there's a component you expect to survive, say 15 years, whereas in a 20 year life you change it around the year 10 so that you use two components for the life, you might decide to leave that until the year 15 to maximize the use of that component for 30 years instead. You can optimize a lot of things like that.” OEM O&M company

Better fault diagnostics and remaining useful life predictions are being developed, to increase reliability when compared to inspection and the use of historic data. This is thought to enable confidently running drivetrain components for longer and lower costs during lifetime extension (Nejad et al., 2022). With more than 50% of gearbox faults caused by bearings, bearing fault diagnosis is especially important in predictive maintenance; therefore, Zhao et al. (2024) use a combination of acoustic signals and AI to identify faults earlier. Other technological solutions are also being used, including improved lubricants that protect and support self-repair (Bill and Bill, 2022). This technology uses a microparticle-based phyllosilicate-additive in lubricants to decrease failure probability of bearings and enable lifetime extensions up to 17.3 years.

Evaluating structural integrity is important for lifetime extension decisions. Foundations and towers are the main components affecting lifetime extension when considering the structural integrity of turbines (Grieve et al., 2017). Grieve et al (2017) propose an evaluation method for turbine towers based on finite element analysis and wind speed/direction history (from SCADA) to compare insights to the reference design. The results show that wind direction is the most important factor in damage accumulation and even using crude wind rose data could determine the lifetime extension potential of a wind farm, however this was only tested on one wind farm.

Hlaing et al. (2024) investigated a virtual monitoring approach to inform “lifecycle management decisions” including lifetime extension for offshore wind. The data input for this method was initially based on sensor data for fatigue load monitoring. The sensors were found to be prone to deterioration in the offshore environment, though could offer valuable information by directly monitoring strain gauges; as a more general point, sensor accuracy, reliability and durability is

a wider issue (Oh et al., 2024). The research then switched to SCADA data to train a probabilistic model. Neither Grieve et al. (2017) nor Hlaing et al. (2024) resulted in practical results such as estimating the number of years of potential lifetime extension.

Intelligent and internet-based solutions are upcoming. Oh et al. (2024) raise Internet of Things based solutions combined with real-time signal processing and predictions to inform maintenance (possibly with AI), while Peng et al. (2023) discuss intelligent O&M (iO&M) as a new area of opportunity especially for offshore wind. iO&M systems can be divided into the online monitoring and diagnosis and offline maintenance parts (Peng et al., 2023). While iO&M can be a way of saving costs, there is a risk of higher costs as well (Peng et al., 2023), as costs for iO&M can increase due to growing scale. More turbines will translate into the requirement of more equipment for iO&M. Significant investments into networks, data storage, software, hardware and sensors are necessary, with further operational costs to keep systems up to date. Moreover, iO&M will require professional technical staff to manage, operate and maintain the systems. Such cost dynamics may be a consideration for other interactive approaches as well (Oh et al., 2024) alongside data security challenges.

These literature findings are supported by the stakeholder interviews, where condition monitoring was consistently identified as an increasingly useful tool to aid repair and maintenance strategies, but there is contrast in its deployment. It is common for asset owners with larger portfolios to have condition monitoring systems installed across their portfolio. This data is typically analysed by a dedicated team, with several responses explaining that there are benefits to aggregating data over a large number of wind farms and that improves the possibility of identifying trends in failure rates and modes.

“It’s a little bit hit and miss. If you’re sat on one wind farm, it’ll feel like magically things are popping left, right and centre without any rhyme or reason. But obviously once you start to stack that data across the fleet, then patterns do appear in terms of age or weather conditions or whatever that might trigger failures and then you can try to get ahead of it.” OEM O&M company

Conversely, smaller asset owners and independent service providers do not typically fit condition monitoring systems. O&M contracts are typically 3-5 years, whereas benefits and costs of such systems are spread out over the asset’s life.

Knowledge sharing on failures and condition monitoring data is not common, with commercial sensitivity around the data (particularly from OEMs) being considered saleable intellectual property. This can be a barrier for smaller companies or those based in emerging markets to implement a proactive repair and maintenance strategy.

2.1.3 Summary of potential for repair and maintenance

To assess the potential for repair and maintenance to extend existing wind turbine lifetimes, evidence was synthesised from literature and stakeholder interviews. The review does not provide a single, definitive quantification of how much O&M can extend the lifetime of wind assets. However, it identifies O&M activities as a necessary enabling factor for lifetime

extension. With the extent of achievable extension typically contingent on asset condition, data availability, component integrity, and regulatory requirements. Extensions of 15+ years on an original design life of 20-25 years were discussed as achievable in literature, supported by examples of current practice raised in stakeholder interviews. However, considerations, such as potentially rising maintenance costs, availability of spare parts and financial viability, complicate lifetime extension decisions. The evidence suggests lifetime extension is best represented through scenario-based lifetime assumptions rather than a continuous function of O&M input.

2.2 RQ 1b: Net-impact on material demand

Extending the operational lifetime of wind turbines can significantly influence the potential for material recovery and recycling relative to a business-as-usual scenario in which turbines operate only within their originally permitted lifetime. However, it is important to bear in mind that the manufacturing of components for wind turbines in the UK is limited and, therefore, closed loop recycling of turbine materials into new turbines within the UK is not currently likely. Moreover, the literature base for this topic is limited. This section covers insights in brief, with more details on material flows across onshore and offshore wind covered in section 2.4.

Lifetime extension may be able to significantly reduce initial waste flows and resource use (Gode and Aspelund, 2024), however it will not prevent them. Global studies primarily focus on scarce and critical materials. For example, Schlichenmaier and Naegler (2022) estimate that lifetime extension by 25% could reduce demand for 25 potentially scarce materials by 5-15%. The impacts of lifetime extension are modest due to relatively long lifetimes already implemented in the wind industry, alongside ambitious deployment targets. In the very long run, when every technology has undergone multiple replacement cycles, a lifetime extension by a factor of 'x' is expected to reduce material demand by a factor of '1/x' for all materials (Schlichenmaier and Naegler, 2022).

Looking at country level studies, Jiang et al. (2025) analysed material flows for wind turbines in Canada, combining historical data with future energy projections (1993-2050). Existing assets are all onshore, but some future offshore wind was included. Life extension was included as part of the sensitivity analysis. For existing assets, the average lifetime was 20 years, but for future projections, lifetimes of 25 and 30 years were also considered. Extending the lifetime of wind turbines to 25 years decreased total future material demand by ~13%, Rare Earth Element (REE) demand by ~10%, total future material outflow by ~27%, and total closed-loop recycling by ~28%. Further extending the lifetime to 30 years amplified these reductions to ~20% in future material demand, ~15% in REE demand, ~42% in total future material outflow, and ~44% in closed-loop recycling.

Lifetime extension provides significant waste savings, with these savings dominated by concrete via foundation reuse for onshore wind assets. In the offshore environment, a study by The Crown Estate (2024) showed that lifetime extension can avoid 136 tonnes steel, 8 tonnes glass, and 4 tonnes polymer of material use per MW (Stravens, 2025). Lifetime extension

reduces demand for new tower and foundation materials (primarily concrete and steel). However, it does not entirely reduce demand for nacelle, blades, hub, or drivetrain components, as these will be required as part of routine O&M activities to support life extension or partial repowering and which may be reused from other wind farms or newly manufactured.

2.2.1 Summary of net-impact on material demand

The impact of wind turbine lifetime extension on material demand is unclear, with a relatively thin evidence base to build upon. The effect on resource security in the UK is, nevertheless, likely to be limited due to low domestic wind manufacturing capacity. In the medium to short term, extending the operational lifetime of wind assets can reduce primary material demand. However, these savings are strongly context-dependent and diminish under high deployment growth, meaning lifetime extension delays rather than eliminates material demand. Global studies suggest that lifetime extension can reduce material demand by 5-15%, with more significant reductions in the long term. Country-level studies show that extending turbine lifetimes decreases material demand and waste, such as in Canada, where a 30-year extension reduced material demand by 20%. The evidence supports representing lifetime extension as a scenario-based demand-reduction factor, rather than a fixed or universal parameter.

2.3 RQ 1c: Net-impact on emissions

The net-impact on greenhouse gas (GHG) emissions was reviewed from 20 publications with information related to wind energy production emissions, specifically equivalent carbon dioxide (CO₂e), from extending the lifetime of existing onshore and offshore wind assets. Three articles based the analysis within the UK. There was a wide range of other locations used within the literature, such as China, Denmark, Norway, Italy, Canada, Germany and the US. A small set of articles did not specify a location. Four articles used offshore wind as the primary generation technology, eleven used onshore wind and five used a mixture of both offshore and onshore wind.

2.3.1 Lifetime extension

Many articles in the literature base did not directly include life extension within the main research, but this was typically included in a sensitivity analysis following the primary analysis. The lack of available primary data required to complete an LCA was a commonly observed challenge, resulting in many assumptions needing to be made. A few novel LCA methodologies for reviewing sustainability options for onshore wind were also reviewed, but these were not specifically on life extension. Finally, several LCA articles covered the impact of alternative sustainability options for wind energy assets, such as component replacement, recycling and repair, without directly including an extended lifetime.

Where a sensitivity analysis was used, increasing lifetime typically showed a decrease in emissions per total wind farm energy production. For example, Li et al. (2022) incorporated

lifetime variation within a global offshore wind LCA sensitivity analysis. Their results indicate that extending the assumed operational lifetime from 20 years in 2020 to 25 years in 2040 reduces total GHG intensity by approximately 11%. Similarly, Bai et al. (2023) identified lifespan extension of power plants as a mechanism for reducing overall energy system GHG emissions in China. Although the contribution of individual technologies was not disaggregated, wind power formed part of the six-generation technology mix considered, reinforcing the broader system-level relevance of operational longevity.

A more technology-specific perspective is provided by Jiang et al. (2025), who analysed historical wind power data in Canada and modelled future projections with extended lifetimes. While existing assets averaged a 20-year lifetime, scenarios of 25 and 30 years were evaluated. Extending turbine lifetime to 25 years reduced CO₂e emissions by 9.16% and energy consumption by 9.89%, with further extension to 30 years amplifying reductions to 14.29% and 15.41%, respectively. These findings demonstrate a clear, incremental relationship between lifetime extension and environmental benefit.

Industry analysis aligns with these academic findings. Vestas (2019) presents a comprehensive LCA of the V150-4.2 MW turbine using a 20-year baseline lifetime. Sensitivity results indicate that shortening the lifetime by four years increases potential environmental impacts by approximately 25%, whereas extending it by four years decreases impacts by around 17%. Collectively, these studies demonstrate that, although often treated as a secondary parameter, operational lifetime exerts a significant influence on life cycle emissions intensity and broader environmental outcomes.

In contrast to studies where lifetime was addressed only through sensitivity testing, several articles positioned life extension as a central component of the research design. These studies explicitly evaluated how extending operational duration alters life cycle environmental performance, embedding service life assumptions directly within the core analytical framework rather than treating them as peripheral adjustments. For instance, Sacchi et al. (2019) conducted detailed LCAs for five wind turbine configurations in Denmark, ranging from 100 kW onshore systems to 2 MW offshore installations. Across all turbine types and capacities assessed, service lifetime was shown to exert a substantial influence on GHG emissions per kWh generated. The consistency of this effect across differing scales and technologies reinforces the structural importance of operational duration in determining emissions intensity.

Similarly, Alsaleh et al. (2019) undertook an empirical assessment of a 2 MW onshore wind farm in the United States using OEM data. In modelling extended turbine lifetimes, the study explicitly accounted for factors such as increased maintenance requirements, additional material inputs, and transport of supplies to the site. Results indicate a progressive improvement in life cycle energy performance with longer service periods: turbines operating for 20, 25, and 30 years produced approximately 3.2, 4.2, and 5.1 times more energy than they consumed over their respective life cycles. Together, these findings demonstrate that when life extension is treated as a primary research variable, it consistently emerges as a key determinant of both emissions intensity and overall energy return.

Some articles within the literature base focus on topics out with LCA, but provide some relevant information. Although the article is mainly focused on wind power decommissioning waste quantification, Tota-Maharaj et al. (2021) provide useful insights into potential life extension impacts. This states that the highest material intensity within a turbine is concrete and steel, primarily located in the tower and foundation. If these two components can be reused for an additional 10 years, the material impact from specific part repowering is minimal and accounted for within the foundation and tower reuse benefit.

The Crown Estate also suggested that life extension of a typical offshore wind farm could postpone 470 tonnes CO₂/MW which would have been emitted with decommissioning (Stravens, 2025). Kasner (2022) found that partial repowering gave the most environmental benefit for the smallest material investment.

The review findings are clear that life extension is estimated to decrease lifetime emissions. This is the case for both onshore and offshore sites, various geographic locations and turbine models. While site repowering was outside the scope of this study, it is important to consider the findings in a wider whole-system emissions context. Lifetime extension may delay emissions associated with new manufacturing and installation activity, however, it can also slow the rate at which additional low-carbon generation capacity is added to the system compared to repowering scenarios. In contrast, repowering existing sites with larger, more efficient turbines has the potential to significantly increase energy yield and displace fossil fuel generation more rapidly. For high-quality wind resource sites in particular, this may result in greater cumulative emissions reductions over the longer term, despite higher near-term material and construction requirements. The optimal approach is therefore likely to be site-specific, depending on wind resource quality, asset condition, and wider system requirements.

2.3.2 Limited LCA and circular strategy information

A potential lack of LCA primary data and information about offshore wind circular economy strategies was highlighted in some of the articles. Gode et al. (2024) conducted a systematic literature review that addresses availability, heterogeneity and development of circular economy strategies in the offshore wind industry. The review found that academic literature on circular economy for offshore wind is typically fragmented and limited, especially on practical insight into refurbishing, decommissioning, and life extension. An example of this being a lack of reliable and accurate information on transboundary effects, such as the effect of physical distance on transporting waste to recycling or waste management plants. Similarly, Brussa et al. (2023) noted the results from their current floating offshore wind LCA work are affected by several limitations due to the lack of available primary data, having to rely on literature and databases. Additionally, to include all the life cycle stages from cradle to grave, several assumptions were required throughout the research that were not completely supported by the case study documentation. Finally, another life extension analysis showed disparities in emissions even between turbines of similar power output (Sacchi et al. 2019). Due to this, the study suggested a move away from generic turbine models within wind energy LCA.

The findings around data scarcity are supported by stakeholders, who stated that very little evidence is routinely gathered by any part of the industry or supply chain on the materials or emissions impact of life extension. One exception was an asset owner who stated they are starting to track emissions savings from its activities, with the anticipation this data may be used by stakeholders involved in the offshore consenting process. A long operating life was identified by one stakeholder as an opportunity to reduce the “carbon cost” of power generation.

“A lot of the carbon cost of the turbines is in material gathering and installation and the actual operating of the turbines in terms of carbon is very low. There's obviously oil and lubricants and fuel to visit the turbines. But it's in the grand scheme of things, a very small wedge, 10% of the wedge, and you've already spent a lot of the money to get the turbines there in the first place. So it makes a lot of sense to have them designed for longer, of course, straight out-of-the-box.”
OEM O&M company

Reuse of parts from aging turbines is viewed as a positive action, both in terms of carbon impact and through the localisation of refurbishment activity, rather than sourcing new parts from a global supply chain.

“...it comes from both a desire to reduce our carbon footprint because we don't want to be responsible necessarily for transporting large components and parts and turbines overseas, we'd like to keep that as local as possible to limit that impact, but we also want to add value back into the UK economy as well. So that's why we prefer to focus on localized options.” Onshore asset owner

There are differing perceptions of “circular” activities in different industry settings and sub-sectors. For example, it is common for long-standing industrial refurbishment facilities to not refer to any language around a circular economy, and their tasks are regarded as business as usual (BAU).

Several parts of the supply chain mention direct dialogue with OEMs on sustainability issues as challenging, with the focus and responsibility for end-of-life decisions sitting almost exclusively with the operator or asset owner. Some OEMs produce LCAs as part of their product brochures, but these do not include detailed consideration of decommissioning pathways. This is contrasted with other sectors where Extended Producer Responsibility and recycled content targets is driving a direct feedback loop with manufacturers. A specific observation from a waste management stakeholder is that the wind industry is behind the construction sector in terms of measuring circularity on end-of-life projects, observing that on building developments, reuse and other circularity options now often are linked to planning permissions and project planning.

For the offshore industry, it is commented that there is a lack of detail and clarity on circular economy within government decommissioning guidance for offshore renewable energy installations, both for England and Wales, and Scotland. As a result, asset owners are working

to find their own solutions, rather than an industry-wide approach, and the lack of real project experience raises a lot of uncertainty about the processes and costs involved.

The findings suggest a general lack of detailed information to complete accurate LCAs including all life cycle stages for some technologies. However, it was also suggested to deviate from generic turbine modelling due to the varying emissions impact for different turbine models of the same power output.

2.3.3 LCA methodologies

The literature identified some novel approaches to LCA modelling of circular economy strategies. Although life extension is not considered, a dynamic LCA methodology was outlined, taking into account future changes in technology, comparing partial and full repowering of a 3.3MW onshore German wind turbine (Heidak et al., 2025). Given the longevity of wind turbines, life-extending measures such as partial repowering and the recycling of dismantled materials are implemented only in the distant future, typically a minimum of twenty years after the initial installation. A comparison of full repowering with partial repowering was conducted, revealing that full repowering is the preferred option from a GWP perspective, due to the larger amounts of electricity produced after the introduction of the measure in 2042. Compared to the partial repowering case, the higher absolute emissions resulting from the demolition, recycling, and new construction of the new plant resulted in a higher benefit according to the findings of this study. The technological progress and the decarbonization assumed in the underlying scenario in accordance with the Paris climate targets contributed to these results. Even when weighting methods such as discounting emissions in the more distant future were applied, these results remained robust or were even reinforced. While the study acknowledges limitations in fully dynamic impact assessments, it highlights the potential of emerging tools such as `bw_timex` to address these challenges. It would be useful to have further LCA studies that more broadly investigate the use of this integrated approach versus the state of the art to demonstrate the quantitative effects and associated changes for the derived conclusions. Finally, Modu et al. (2025) outlined a method to assess the reuse of existing onshore wind foundations during repowering, but provided no discussion of wider GHG implications.

2.3.4 Alternative sustainability options

Although life extension is not mentioned within all of the reviewed articles, various other sustainability options for end-of-life wind energy assets are considered. Schreiber et al. (2019) considers the environmental impact of component replacement without including a longer asset life. Taking component replacement into account, the total environmental performance worsens by 14.4%, 18.6% and 18.9% for DFIG, Direct-Drive Synchronous Generator (DDSG) and Direct-Drive Permanent Magnet Synchronous Generator (DDPMSG). The impact categories are primarily increased due to the additional steel and copper production. Zhuo et al. (2023) also considered the impact of generator types. The study presented a carbon emission for a 2.5-MW doubly fed asynchronous wind turbine of 10.43 g/kWh. In comparison,

the carbon emission of a directly driven permanent magnet wind turbine with the same power is 8.48 g/kWh, a difference of only 81.4%.

Jacobs (2025) carried out emissions modelling using a reference 2MW wind turbine. Instead of alternative end of life (EoL) scenarios, this focussed on the embodied carbon of the existing asset, the carbon benefits of recycling materials, and transportation emissions considerations. Zero Waste Scotland (2024) found benefits from using refurbished or recycled materials, estimating a reduction to the carbon footprint of a turbine by 35%.

A comprehensive wind turbine LCA produced by Vestas (2019) included various examples of the impact of alternative sustainability methods. The repair of major components was included where previously it was assumed that all service parts were replaced with new parts. This included change of oil and filters, and renovation/replacement of worn parts (e.g. the gearbox) over the lifetime of the windfarm. The transport associated with O&M, to and from the turbines, is included in this phase and has been updated to reflect typical vehicles and servicing. The LCA model for disposal of the turbine accounts for specific recycling rates of different components, depending on their material purity and ease of disassembly, based upon industry data. At end-of-life, full credits are given for the material recovered (i.e. relating only to metal parts made of steel, iron, copper and aluminium), which is based upon an 'avoided impacts approach' to providing credits for recycling. Frequency of repaired parts was also included in the sensitivity analysis. Doubling of replacement parts has the effect of increasing some impact categories up to 20%.

The emissions impact of specific components is also considered by Stavridou et al. (2020). In this study the LCA of two onshore wind turbine tower configurations is performed. Both towers are of 76.15m height and their structural analysis results have proved that they can both accommodate the same rotor with similar efficiency. A preliminary study is performed where all life stages from production of the materials to the end-of-life have been considered. The connection of the turbines to the grid is not examined in the present study while the lifetime of the turbines is set to be twenty years. The distribution of the CO₂ emissions per lifetime stage is presented, where the steel parts construction has been proved to have the highest environmental impact.

2.3.5 Summary of net-impact on emissions

The net impact of life extension on GHG emissions in wind energy was examined through reviewing several LCAs which discussed life extension, although many treated it as part of sensitivity analyses. Extending turbine lifetimes typically reduces emissions per unit of energy produced. Extending the lifespan of turbines, especially through component refurbishing and material recycling, is projected to reduce carbon footprints significantly, with estimates suggesting reductions of up to 35% in emissions and postponed emissions of ca. 470 tonnes CO₂/MW due to delayed decommissioning. However, there is a lack of comprehensive data on circular economy strategies in offshore wind, especially on reuse, refurbishing, lifetime extension and decommissioning, suggesting a need for further research. Alternative sustainability strategies, like component replacement combined with lifetime extension, also

contribute to emission reductions. Recycling materials at the end of a turbine's life completes emissions reductions, especially metals recycling. Lifetime extension, partial repowering, repair and recycling are crucial for reducing emissions, but further research is needed to refine lifecycle assessments and to better understand long-term environmental benefits of these strategies.

2.4 RQ 2a: Potential for component reuse and material recovery

A sizeable literature base of over 50 publications was reviewed relating to component reuse and material recovery from existing wind assets in either the UK or as proportions for current capacity stocks in other countries. About half of the literature presented quantitative estimates of component reuse and/or material recovery, but only a few focused on the UK with others covering Germany, Denmark, Europe, US or taking a global or no specific geographic focus. The remainder included supporting information mostly for onshore wind or wind in general. Interviewees highlighted that the UK supply chain for wind turbine materials shows varying levels of maturity. Steel recovery is well established, with towers and monopiles largely recyclable, though much of the material is currently exported for processing before returning as manufactured products. Concrete foundations are commonly partially removed and recycled locally, by removing steel rebar and crushing the remaining material for use as aggregate. One interviewee highlighted there may be some potential for foundation reuse in site-specific circumstances. Blades remain the most challenging component, with limited UK recycling options and long-term solutions still scaling up from research, making near-term disposal reliant on mechanical recycling or, in some cases, incineration with energy recovery.

2.4.1 Material flow estimates

2.4.1.1 Wind farm portfolios

2.4.1.1.1 [Studies combining onshore and offshore wind portfolios](#)

Based on five LCA's on wind turbines in Denmark with capacity ranges of 100kW to 2MW, Sacchi et al. (2019) present material intensity data observing that material mass of onshore wind turbines has decreased over time and with size. The amount of low-alloy steel needed for the wind turbines in the 100kW set is about 150 kg per kW of nominal power output, with large variations around that value. For the wind turbines in the 2MW set, this value decreases down to approximately 100 kg of steel per kW on average. This also applies to blades. An average of 9 kg of reinforced plastics are needed per m² of swept area on wind turbines from the 100kW set (with a total swept area of 320-350 m²); with the figure down to 5.5 kg for wind turbines that belong to the 2MW set (with a swept area of 5000-7000 m²).

Shammugam et al. (2019) review German future deployment scenarios until 2050 and their associated metal requirements (steel, copper, nickel, dysprosium) across three different deployment scenarios (BAU, advanced, innovative). The system boundary of the analysis covers the rotor, nacelle, tower and foundation for both onshore and offshore installations in

Germany, including eight different generator types of which two are future technologies. Average material compositions of wind turbines were derived from LCA reports and manufacturer's sheets of turbines. An upscaling method was applied to the components to estimate weights of future turbine designs. In order to determine the annual material demand, the specific material demand and their respective market shares were multiplied by the projected installed capacity of wind turbines. Three energy scenarios for Germany, published from 2014 onwards were selected: GROKO (Nitsch, 2014), IEE (Fraunhofer IWES et al., 2015) and REMod (Henning and Palzer, 2015).

Results show that steel is the most intensively required material for the deployment of wind turbines, followed by copper and alloying elements such as chromium, manganese and nickel. Based on the results, copper and dysprosium are identified as the most critical metals particularly due to the high demand with respect to the current availability and lack of feasible and economic measures to mitigate the possible supply risks in the future.

The article discusses the opportunity for recycling to fill the supply gap of materials. Recycling rates of wind turbines were based on (Andersen et al., 2014) – which are High alloyed steel (98%), Low alloyed steel (95%), Cast iron (95%), Aluminium (95%), Copper (98%), PCB (50%), Magnets (98%) – and have not been validated with empirical data. Overall, approximately 45-60% of copper demand between 2018 and 2050 across all scenarios can be recycled. Conversely, the recycling potential of dysprosium is much lower, as only 20-32% of the total demand would be available for recycling between 2018 and 2050. This is due to the current market share of drive trains with permanent magnets being low, with the expected large-scale offshore expansion materialising in the future. The in-use stocks are expected to grow and would be available for recycling beyond 2050.

Although there are already established markets for scrap metals, turbine recycling is still at an early stage of development, in particular, the reprocessing of REEs is still highly limited by process costs and output quality (Binnemans et al., 2013; Royen and Fortkamp, 2016). It is widely recognised that recycling metals requires considerably lower energy intensity and produces fewer emissions than virgin material manufacturing (Meng et al., 2025). There are companies in the UK that can recover and recycle many metals back into domestic manufacturing supply chains. Support of and investment in these pathways would reduce the UK's reliance on material imports, decrease waste export and support growth across the country.

Metals also featured in two further studies focused on Canada and the EU. Jiang et al. (2025) present a material flow model for wind turbines applied to Canadian historical wind turbine construction data alongside future wind energy projection (1993 – 2050). Existing assets are all onshore but some future offshore assets are included. Lifetimes of existing and future assets were assessed using a Weibull model, with the shape parameter for both onshore and offshore wind turbines set at 4.07 and average lifetime of 20 years. Converse to other studies that either increased or decreased material intensity, this study kept material efficiency relatively stable, changing from 698 tonnes per MW in 2020 to 693 tonnes per MW in 2050. In contrast, for offshore wind turbines, material efficiency was expected to decrease significantly, from 502

tonnes per MW in 2020 to 642 tonnes per MW in 2050. This is because turbine capacity is expected to increase more rapidly than rotor diameters and hub heights. Different EoL scenarios are modelled through to their input on secondary supply. Closed-loop recycling could offset 3.95-9.36% of cumulative total material demand (0.33 - 7.38% for REEs), depending on the input parameters. This is similar to the findings from studies for other countries and regions, the significant increase in material demand from wind energy system development cannot be offset by domestic closed-loop recycling in the first half of the century. The authors argued that reusing permanent magnets is preferable, but decommissioned magnets may not align with future turbine designs.

Godoy León et al. (2025) analysed material flows for six key metals (nickel, manganese, neodymium, aluminium, copper, and iron) for two different generator types (direct drive and gearbox) in 2016 (EU28) and 2021 (EU27), based on existing papers to source data which was presented in a multi-layer material flow diagram (turbine, gearbox, selected materials) at EU level. The study includes both onshore and offshore wind turbines, covering major components (rotor, nacelle, tower, foundation) but not inter-array and export cables and substations. Similar to other studies, a high recycling efficiency was assumed for metals (Steel 90.4%, iron and cast iron 98.5%, copper 98%, aluminium 76%) but a lower rate for plastics (Polymers 59%).

The post-use phase for 2021 reveals that 88% of the end of use material originates from component failures, while 12% is from decommissioning. Nacelle decommissioning contributes significantly, representing 36% of the total mass. However, this does not account for concrete or scour protection material; including these would shift the majority of the mass contribution to the tower and foundation. Approximately 51% of the material from decommissioning comprises of unalloyed or low-alloy steel, with carbon steel making up 63% of the total decommissioned mass. For component failures, 58% originate from the direct drive generator, and 33% from the gearbox (17%) and generator (16%) in gearbox technology. Predominant materials in these components include unalloyed or low-alloyed steel, high-alloyed steel, and cast iron, which makes iron the element with the most substantial contribution. Figures for 2016 were similar.

Over time, flows into the use-phase have seen an increase ranging from 39% to 42% for gearbox turbines and from 18% to 42% for direct-drive turbines, depending on the specific metal. Meanwhile, end of use flows have risen significantly, with increases of 62% for nickel and manganese and 92% for aluminium in gearbox turbines. In direct drive turbines, end of use flows increased by: nickel 76%, manganese 69%, and aluminium 88%. These trends highlight the growing material demand and the corresponding rise in materials reaching the end of use phase as wind energy capacity expands.

Taking a global perspective, Meng et al. (2025) identify six material groups that are used in onshore and offshore wind, namely steel, iron, composites, REE, concrete and other metals. The authors appear to make a “90/90” argument: they pose that 90% of materials by volume are steel and concrete, and that 90% of material volume is generally recoverable. However, the narrative goes on to suggest otherwise, with the primary focus on material recovery and some component reuse.

Four of the identified six material groups are reviewed (steel, composites, concrete, REE-magnets). Steel, if used from recycled sources, can save up to 70% of energy demand and 58-70% GHG; 1 tonne of recycled steel can save 1.5 tonnes CO₂, 1.4 tonne iron ore, 740 kg coal, 120 kg limestone – when compared to virgin steel. Average post-consumption recovery is 80% while 85-90% of steel from construction and automotive is generally recovered. In the case of composites, both glass and carbon fibre composites are still considered hard to recycle; This is due to a lack of dedicated commercial scale facilities (Green Alliance, 2026). According to the authors, even the DecomBlades’ glass fibre recycling solution is expected to only replace up to 5% of raw materials in new blades. While closed loop composite recycling within the wind industry may be limited, research continues to investigate other potential manufacturing sectors, such as automotive and construction, that can utilise recovered materials.

Details about the potential for magnet recycling were unclear, without potential recovery rates from recycling solutions and system boundaries for cited environmental assessment excluding magnets pre-processing steps. Concrete use is prevalent, in onshore wind ca. 70% of material use is concrete found primarily in foundations. Onshore foundations are thought to have a lifetime of 60 years and offshore about 50 years, but reuse was considered difficult for a host of reasons. Material savings through concrete recycling is limited, as the review suggests that 80-100% is downcycled to aggregates (e.g. for roads).

Tota-Maharaj and McMahon (2021) quantify waste from UK wind turbine decommissioning, projecting annual waste to rise from 35kt (2015-2019) to over 1,200kt by 2039. Following earlier wind deployment statistics, concrete dominates early waste streams while steel becomes prevalent with offshore growth. Six scenarios explore reuse, recycling, and heat recovery, demonstrating significant landfill reduction and GHG savings. Material composition data and capacity data were combined with baseline UK recycling rates, to calculate material recovery figures. Baseline assumptions were 90% recycling of metals, with concrete foundations left in the ground and blades going to energy recovery or landfill. The study analysed scenarios in two categories on potential component reuse and material recovery (Table 3 and Table 4).

Table 3: Three potential component reuse scenarios were assessed in Tota-Maharaj and McMahon (2021).

Potential Component Reuse (Scenarios 1–3)	
Scenario 1 — Reuse of whole turbines (second-hand turbines)	<p>Assumes 10% of turbine components (excluding foundations) are reused for an additional 10 years.</p> <p>5% reused in the UK (reduces waste by 50%), 5% overseas (reduces UK waste by 100%).</p> <p>Foundations cannot be reused and are excluded.</p> <p>This reduces the need for new turbines and lowers associated embodied carbon.</p>

Potential Component Reuse (Scenarios 1–3)	
Scenario 2 — Remanufacture and reuse of components	<p>Also assumes 10% of applicable components are remanufactured and reused.</p> <p>Within wind industry: all parts except blades and foundations qualify.</p> <p>Outside wind industry: all parts except blades, towers, and foundations qualify.</p> <p>Components reused in either case reduce associated waste by 100%, since they replace the manufacture of new parts.</p> <p>Blades are excluded because composite blades cannot be remanufactured.</p>
Scenario 3 — Lifetime extension (repowering)	<p>Assumes 10% of turbines undergo part-repowering that extends operational life by 10 years.</p> <p>Only towers and foundations are reused.</p> <p>This saves 5% of tower and foundation waste (10% of turbines × 50% lifetime extension).</p> <p>Provides substantial concrete mass savings, though steel dominates carbon savings.</p>

Table 4: Three material recovery scenarios were assessed in Tota-Maharaj and McMahon (2021).

Material Recovery (Recycling & Heat Recovery Scenarios)	
Scenario 4 — Recycling composite materials into aggregate	<p>Composite materials (primarily blade waste) are processed into aggregate.</p> <p>Reduces landfilling of composites and avoids demand for virgin aggregate.</p> <p>Provides measurable GHG savings through avoided virgin aggregate production.</p>
Scenario 5 — Recycling concrete and steel from foundations	<p>Focuses on recovering concrete and steel, especially from foundations.</p> <p>Concrete contributes most to the mass recovered.</p> <p>Steel contributes most to the embodied carbon savings due to its high carbon factor.</p> <p>Assumes foundations can be demolished and recovered onshore; offshore recovery of piles remains uncertain.</p>
Scenario 6 — Combined composite recycling and heat recovery	<p>Treats 50% of composite material waste.</p> <p>35% incinerated for heat recovery; 65% recycled into cement production.</p> <p>Carbon savings are not calculated due to data gaps, but the process reduces the need for virgin cement inputs.</p>

2.4.1.1.2 Onshore wind studies

Kramer et al. (2024) investigated circular economy pathways and material flows for decommissioned onshore wind in Germany and Denmark, finding that approximately 50-60% of the decommissioned turbines were exported for a second life elsewhere. Volumes to estimate blades for recycling were analysed, forecasting between approximately 380–770 tonnes for Denmark and approximately 4,400–11,300 tonnes for Germany in the next decade.

In January 2022, Denmark had 4,712 MW installed capacity in land-based operations, represented by 4,186 turbines and 51,016 tonnes of blade mass. The average age of the operational turbines was 21 years and 74% of operational turbines reached or exceeded the 20-year design lifetime. The fraction of turbines older than the design lifetime was 40% and 30% based on installed capacity and blade mass respectively. Decommissioning has taken place since 1998, totalling 826 MW, which corresponded to 3,195 turbines and 7,131 tonnes of blade mass. The average age of the decommissioned turbines was 18 years. In the next ten years, ~950–1,900 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 approximately 380–770 tonnes per year for the domestic recycling industry.

In Germany, there was 59,231 MW installed capacity in land-based operation by June 2023, represented by 28,611 turbines and 738,719 tonnes of blade mass. The average age of the operational portfolio was nearly 15 years and 29% of total operational turbines were 20 years or above. The fraction of turbines older than the design lifetime was 15% and 11% based on installed capacity and blade mass respectively. Expected decommissioning was steadily increasing with approximately 8,900–22,600 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, approximately 4,400–11,300 tonnes per year would potentially enter the blade-recycling stream in the next ten years.

Recycling rates can help in forecasting the scale of material flows. Li et al. (2021) assume ambitious recycling rates for the recovered ground surface equipment and facilities in China, assuming 85% steel and 90% copper in the wind turbines, substations and other equipment to be recycled. All underground materials though, were not included in the recycling rate. Similarly, Alsaleh and Sattler (2019) assume >90% recycling for metals and plastics, with the remainder landfilled.

Jacobs (2024) analysed onshore wind decommissioning in Scotland, based on two scenarios:

- Low = 30% of operational turbines are repowered after 20 years of operation, 20% repowered after 25 years; 20% decommissioned after 25 years; and 30% decommissioned after 35 years.

- High = 25% repowered after 15 years; 25% repowered after 20 years; 25% repowered after 25 years; 15% decommissioned after 25 years; 10% decommissioned after 35 years.

The assessment used average weights for set turbine size categories based on turbine models in the RUK database where information on the total weight is available. The assessment excluded foundations, aluminium and REEs. The modelling results showed that between 1.26 million tonnes (Mt) (low) and 1.40 Mt (high) of materials would be released via onshore wind decommissioning in Scotland by 2050. The decommissioning of a small number of sites with >100 wind turbines significantly influenced the timing of material yields.

Similarly, ZWS (2024) estimated a material recycling flow of approximately 1.2 Mt from onshore wind by 2050. The material stream would consist of 956,728 tonnes steel; 120,137 tonnes iron; 79,363 tonnes resin; 52,909 tonnes fibreglass; and 20,175 tonnes copper. This would be generated from 4,894-5,613 onshore turbines that are forecast to be decommissioned between 2021-2050 (each turbine capacity between 0.5-5MW), assuming a 25-years lifetime (ZWS, 2024).

2.4.1.1.3 Offshore wind studies

Li et al. (2022) assessed material demand and recycling output for fixed offshore wind up to 2040, for two global offshore wind growth scenarios and lifetime extension considering heterogeneity of wind turbine generator design and size. They argued that, for fixed offshore wind, mass intensity will increase from 365.2 t/MW in 2020 to 559.6 t/MW in 2040. Similarly, Topham et al. (2019) argued that material intensities would likely increase with larger turbine capacities.

The global fixed offshore wind sector will cumulatively require approximately 192.9 Mt of low-alloyed steel, 8.8 Mt of high-alloyed steel, 12.9 Mt of iron, and 13.4 Mt of concrete in the period between 2020 and 2040 (Li et al., 2022). These trends imply a 55, 49, 55 and 50-fold expansion by 2040 compared to current demands respectively. Putting this further into context, installed volumes of steel in offshore wind monopiles by 2019 across Europe amounted to 0.6 Mt in Germany, 0.2 Mt in the Netherlands and 1 Mt in the UK (Topham et al., 2019) while demand for steel in offshore wind is forecast to grow to 25 Mt by 2050 in the UK alone (Harrison, 2024).

Meanwhile, cumulative demand for other metals (copper, aluminium, chromium, manganese, molybdenum, nickel and zinc) will grow from about 2 Mt in 2020–2030 to about 3.7 Mt in 2030–2040, reflecting an increase of about 85% (Li et al., 2022). The large-scale deployment of permanent magnet generator technologies by 2040 will also require large volumes of other metals (Table 5).

Table 5. Cumulative volume of other metals required in the large-scale deployment of permanent magnet generator technologies by 2040.

Metal	Cumulative volume	Proportion of 2020 production volume
Neodymium	25kt	38%
Dysprosium	2.8kt	24%
Praseodymium	3.8kt	24%
Terbium	1.1kt	26%

Material recovery for the nacelle, rotor, tower, and foundation was also modelled in Li et al., (2022). Modelling focused on 23 materials, excluding concrete and reinforced iron in foundations, embedded in 20 technologies, excluding export cables to the grid, developing three different recycling scenarios: 100% recycling; optimistic; conservative which modelled a range of recycling rates applied to each material. The optimistic scenario modelled that a small proportion of supply of metals between 2020-2030 and 2030-2040 will be met by secondary materials (Table 6).

Table 6. Proportion of metal demand met by secondary materials recovered from wind turbines in from 2020-2030 and 2030-2040.

Metal	Proportion of 2020-2030 supply met with secondary materials	Proportion of 2030-2040 supply met with secondary materials
Iron hydride	3%	10%
Copper	2%	6%
Aluminium	2%	8%
Nickel	2%	7%
Zinc	2%	7%
Neodymium	1%	2%
Dysprosium	1%	2%

Metal	Proportion of 2020-2030 supply met with secondary materials	Proportion of 2030-2040 supply met with secondary materials
Praseodymium	1%	2%
Terbium	1%	2%

Material demand was also found to decrease when wind turbine lifetimes expand from 20 to 25 years. Cumulative requirements declined approximately: iron (7%), steel (7%), concrete (8%), copper (6%), aluminium (6%) and REEs (7%) (Li et al., 2022).

These results suggest that wind turbine recycling can only meet a modest proportion of material demand for the expanding offshore wind industry, and lifetime extension could offer a buffer-effect.

2.4.1.2 Challenging materials flows

In practice and in the literature, two flows are often highlighted as particularly challenging: composites from turbine blades and critical materials from REE permanent magnets. This section will discuss insights from publications about each of these material flows.

2.4.1.2.1 Turbine blade material flows

Understanding future waste volumes for turbine blades is important for value chain stakeholders, such as blade manufacturers, waste management companies and potential waste material off-takers, to evaluate future waste flow potentials from an operational and cost perspective (Lund and Madsen, 2024).

2.4.1.2.1.1 Global insights

Global wind turbine blade waste may amount to more than 2 Mt by 2050 (Liu and Barlow, 2022); Lund and Madsen, 2024). That is a modest forecast when compared to others who reviewed and analysed this topic, finding 30-44 Mt by 2050 (Mishnaevsky, 2021; Harnidl et al., 2025). For each MW of wind installed, it is estimated that 9.6-15 tonnes of composite waste is generated (Bennet et al., 2020; Mishnaevsky, 2021). Annual growth of blade waste is expected to be slow until 2026 and then rapidly increase until 2034.

Global trends in blade waste suggest that China will have the greatest share (40%), followed by Europe (25%) and the USA (16%) (Beauson et al., 2022). Europe will face the blade recycling challenge first though, being early movers for wind deployment. In Europe, Germany will have the greatest volumes the soonest, followed by Spain, Finland, Sweden, and then France, UK, Italy and Romania (Beauson et al., 2022).

Although projected waste volumes from wind turbines may appear substantial, the wind sector is expected to account for less than 20% of the global composite waste market (Harnidl et al., 2025). The main sources of composite waste originate from other sectors, including building

and construction, electrical and electronics, transportation, and marine activities, followed by wind power, production waste, aeronautics, consumer products, and tanks and pipes.

This distribution suggests that the challenge of managing composite waste extends well beyond the wind industry and that several sectors face comparable or greater pressures to develop recycling solutions. At the same time, it highlights potential opportunities for cross-sector collaboration to achieve economies of scale in composite recycling infrastructure.

2.4.1.2.1.2 USA insights

For the US, forecasted numbers of blades removed are comparable across studies, estimating removal of 8,000 (Mishnaevsky, 2021) and 3,000-9,000 (Cooperman et al., 2021) blades per year for 2021-2025. By 2040, 190,000 blades will have been in service for 20 years or longer, and the forecast is that between 10,000-20,000 blades will reach end of use up to that period (Cooperman et al., 2021). That is 5.3-10.5% of blades of the total fleet of blades that have reached the end of their technical design lifetime.

Using a Weibull distribution, Mishnaevsky (2021) compares end of use blade mass for lifetimes of 15-30 years at 5 year intervals. Forecasts show a smoother annual variation compared to blanket lifetime assumptions of e.g. 20-25 years seen in other studies. The total waste volumes for 2050 varies from 1.53 to 2.75 Mt depending on the modelled lifetime. The effect of varying the lifetime duration is highly evident in the near term: compared to a 20-year lifetime, total waste in 2030 increases by 96% for a 15-year lifetime and decreases by 98% for a 30-year lifetime. In a similar ballpark, Cooperman et al. (2021) forecast 1.5 million metric tons by 2040 and 2.2 Mt by 2050 and EPRI (2018) forecast 2.1 Mt by 2050.

In a state level study focusing on Iowa and Missouri, Ghosh et al. (2022) note a limitation in material recovery potential. Assuming that each recycling process would start with a mechanical step, a proportion of the material will be lost during the grinding of blades. The expectation is that the lost material fraction would be captured and landfilled.

2.4.1.2.1.3 European insights

For Europe, estimated blade removal has been 3,800/year, which was about half the volume compared to the US in the same period up to 2026 (Mishnaevsky, 2021). The total volumes of blade waste are forecast to rise steadily to 325,000 tonnes/year by 2050 (Lichtenegger et al., 2020), up from a forecast of 35,000-100,000 tonnes for 2020 (Beauson et al., 2022). There may be substantial fluctuations in annual flows though, as has already been observed due to life extension, and this impacts business case feasibility e.g. for investment in recycling facilities (Lund and Madsen, 2024).

More than half of turbines and blades have the potential to be reused as operational assets (as seen in section 2.4.1.1.2 by Kramer et al., 2024). Moreover, refurbishment of blades may divert another proportion away from the recycling stream. For example, in the Netherlands about 20% of blades are refurbished and resold, both within and outside the EU (Mishnaevsky, 2021).

2.4.1.2.1.4 UK insights

In 2019, there was approximately 10GW offshore and close to 14 GW onshore wind installed in the UK. Overall, there were 2,555 turbines and approximately 7,655 blades installed offshore (Jensen et al., 2020), while onshore there were 8,625 commercial turbines with 25,875 blades (Bennet et al., 2020). Transplanting a similar rule that can be derived from the US (annual retirement rate of 5.3-10.5% of blades >20 years) would suggest a steadily rising waste stream in the UK too.

Sultan et al. (2018) investigated the optimal location for a recycling facility in the UK, depending on the location of waste arisings. They found that the location changes over the years until a threshold is reached with an ideal location in the North of England.

2.4.1.2.2 Magnet material flows

Turning to the potential for component reuse and material recovery from the current stock to meet the demand for future stocks (i.e. RQ 2a) in the case of magnets, a number of recent studies were reviewed. Overall, research does not consider direct reuse potential of magnets in wind and there is pessimism about the potential for recycling of Neodymium to meet material demand over the next decades with values generally below 1% but widely ranging up to about 33-35%. High increases of recycled input rely on the unrealistic assumption of near absent material recovery to 100% recovery from wind. Instead, design interventions are suggested to decrease resource availability risk.

2.4.1.2.2.1 Global insights

Three studies that analyse global material flows of REE (including Neodymium) in the context of the wind industry were reviewed.

Liang et al. (2023) investigated whether metal demand can be scaled up to match the low-carbon technologies required in the aggressive IEA Net Zero emissions scenario, which forecasts a nine-fold increase in renewable energy capacity in 2050, compared to 2020. Their stock and flow model predicts future material demands of several low-carbon technologies and the potential of recycled end-of-life materials. Scenarios for 2050 suggest that extreme increases in recycling can raise input of critical materials into further manufacturing from below 1% up to 35%. An increase to 35% would depend on recovering 100% of REE from wind and 80% from electric vehicles but only recycling technologies for batteries were discussed. Similarly, Schlichenmaier and Naegler (2022) assume an increase of recycling rates to 80% in 2050. Even with such dramatic increases in recycling capabilities, which make a manifold of scalability assumptions of current solutions, primary demand of most materials would be reduced by ca. 33%. Even the full recycling of all infrastructure would only reduce total primary material input for all energy and transport technologies by a maximum of 50% until 2050. This is due to the long-term horizons of most infrastructure.

The model by Schlichenmaier and Naegler (2022) explored global stocks for 25 potentially scarce materials for an energy system that is compatible with the EC 1.5°C global scenario. As part of sensitivity analysis, the effect of a longer technical lifetime was estimated by comparing mineral demand in the standard setup with calculations where the lifetime of each technology

was increased by 25%. Wind technologies were used as input, however, results were not separated out by technology. The supplementary information compiles available literature estimates for the kg/MW of REE for different onshore and offshore wind turbine drivetrain configurations, deriving mean and median values for use within the model. Conversely, the study by Liang et al (2023) did present separate results for the wind industry. Their sensitivity analysis showed that extending the lifetime of wind slowed down initial demand for critical materials but limits potential to feed new demand with secondary supplies. The base model assumed a global increase to ca. 7 GW of wind, of which ca. 1.5 GW is offshore; with deployment growing to ca. 2 GW per 5 years until 2030, and then maintaining ca. 2 GW per 5 years until 2050 with a growing proportion of deployment being replacement capacity rather than new capacity.

Clearly there are limitations to reduce supply risk through recycling. After reviewing the economic potential for REE recovery and recycling, Patil et al. (2022) argue that direct reuse of magnets may be the most economical pathway at end-of-life. Others, however, have highlighted the limitations of magnet reuse (e.g. Meng et al., 2025). Alternative technologies that are not reliant on critical materials could offer another solution to cover the gap between supply and demand (Liang et al., 2023).

2.4.1.2.2.2 USA insights

Modelling of neodymium flows in the USA found an even lower potential to meet demand with recycling solutions. The US offshore wind sector's demand for neodymium will grow significantly by 2050. Even with 100% recycling of decommissioned turbines after a 20-year lifetime, around 80% of the neodymium will still be needed from primary sources (Fishman and Graedel, 2019). Such high recycling rates would depend on technological advancement for recycling.

Fishman and Graedel (2019) argue that design for reuse would be preferable over recycling. But in a slightly contradicting argument, they discuss technology advances using turbine designs with less neodymium per MW of capacity that is being deployed. This would decrease the pressure on supply and, combined with recycling capabilities, enable the replacement of the first generation of turbines with greater capacity in the next generation using the same volume of neodymium overall.

2.4.1.2.2.3 European insights

Godoy et al. (2025)'s study about the EU analysed material flows for metals (including neodymium) for both onshore and offshore technologies based on data from 2016 (including the UK) and 2021 (excluding the UK due to Brexit). Overall, the data showed a material outflow of 1130 kt of which 990 kt was recycled i.e. a performance of 88% overall. However, for neodymium the downcycling rate was 100%, with all material ending up as tramp element in steel. There was no primary or secondary production of neodymium in the EU. This study underlines the importance of realism in calculating the potential to meet demand through wind magnet recycling, as was also hinted at in the global studies above.

Recycling of neodymium is limited, despite the concentration of material within wind turbines which could ease dismantling and collection for recycling purposes. Challenges that may impede recycling include the relatively low price of neodymium, short presence of components containing the material, underdeveloped separation and refining processes, and slow timeframe of establishing recycling facilities of 5-10 years (Yang et al., 2017).

In principle, with a vastly improved recycling performance, the EU's outflow of neodymium could meet 41-124% of demand in 2030 (Godoy et al., 2025). This suggests, though does not explicitly confirm, a similar dynamic as proposed by Fishman and Graedel (2019), where more capacity could be deployed in the next generation of wind farms with a lower material intensity per MW.

2.4.2 Technology to support component reuse and material recovery

2.4.2.1 Blades end of use technologies

Interviewees highlighted blades as a more challenging component to manage at the EoL, with supply chains less established than for other components. References were made to existing facilities within the UK, where commercial blade waste has been processed. However, there was interest in the development of more regional options due to costs associated with transport.

Options of repurposing blades into infrastructure such as benches and sound barriers were also mentioned, however concerns relating to the scalability of this type of solution were raised.

Numerous references were made to research initiatives to develop new technologies and solutions for blade recycling, however the timeframe for scalability and roll out of these was uncertain, with estimates of 10+ years provided before such a facility might be operational. For current and near-term blade waste, stakeholders indicated that options like landfill and incineration were not favourable, and that alternatives like mechanical recycling were preferred. Nevertheless, some instances of incineration with energy recovery were described, suggesting a more mixed EoL processing landscape as reflected by the findings in the literature review.

"It's just blades that remain an issue, everywhere. If they're in good condition, then you might be lucky and be able to sell a blade set with a turbine or to a customer. At the moment we are sitting on several sets of blades, we're still looking for customers and, if not, they will have to be basically shredded." UK O&M company

2.4.2.1.1 Recycling state of the art

The recycling of blades was well addressed in both scientific and grey literature, reflecting the scale of the anticipated quantities and material flows as outlined in Section 2.4.1.2.1. Much of the literature consists of review papers setting out the current state of the art for composites recycling technologies and their applicability for wind turbine blades. (Beauson et al., 2022)

categorized current strategies for blade end-of-life management into design for recycling, reuse, repurposing, recycling technologies, and energy/material recovery. Design-for-recycling approaches aim to facilitate future material recovery through alternative resins, simplified material systems, or improved dismantling processes. However, adoption remains limited and depends on the parallel development of compatible recycling technologies. Reuse and repurposing options, such as reusing whole blades after inspection or cutting them for architectural or structural applications, have demonstrated technical feasibility but implementation is limited due to transport costs, variability in blade condition, and the need for detailed structural assessment methods. The study finds that a wide range of repurposing applications have been investigated and proven in the market but is generally considered for small scale or in combination with recycling solutions.

Recycling technologies are typically categorised as mechanical, thermal, or chemical. Bennet et al (2020) notes that mechanical recycling, shredding or grinding blades into fibres or granulates, is currently the most technologically mature approach, although it produces relatively low-value secondary materials. Thermal processes such as pyrolysis and fluidised-bed treatment aim to recover fibres by decomposing resin matrices, but recovered fibres often exhibit degraded mechanical properties. Chemical methods such as solvolysis offer the potential to recover fibres and resin components with higher purity but remain limited by cost and scalability challenges. Beauson et al (2022) states that for processes involving several preparation and separation steps, such as mechanical, thermal and chemical recycling, the recovered material ends up smaller in size and more uniform. The thus-obtained shredded composites may therefore be easier to reuse in new applications than large blade sections. However, there are no standards framing the characterisation and the properties of recovered materials. Emerging techniques such as plasma recycling have also been investigated; Kusano and Kusano (2024) report promising recovery of carbon fibres with high retained mechanical performance, although the process is currently considered unsuitable for typical wind blade materials due to cost and material composition constraints. Mendoza and Pigosso (2023) conclude that mechanical recycling remains the most viable near-term option, while thermal and chemical routes require further development.

Environmental assessments broadly support this conclusion. Lifecycle analyses by Pender et al. (2024) suggest that mechanical recycling currently provides the most favourable greenhouse-gas performance because it avoids polymer combustion and requires relatively low energy input. However, environmental benefits remain limited because recycled fibres often substitute only small quantities of virgin materials due to quality degradation. Alternative approaches such as cement kiln co-processing, reviewed by Nagle et al. (2020) can utilise shredded blades as both fuel and raw material in cement production, substituting clinker inputs. Nevertheless, concerns remain that adoption of such solutions could discourage the development of higher-value reuse pathways.

Recent research by Revilla-Cuesta et al., (2024) has explored the incorporation of mechanically recycled blade material into construction products such as concrete. Experimental studies indicate that small additions of recycled blade material can reduce cement consumption and associated carbon footprints while maintaining acceptable

mechanical performance under certain environmental conditions. However, material behaviour may degrade under high temperature exposure due to melting of polymer components and combustion of organic core materials. Consequently, the long-term durability and optimal content of recycled blade material in structural applications remain active research topics.

Despite the extensive research portfolio of blades recycling research, Beauson et al. (2022) concludes that currently, few recycling solutions are available at a commercial scale, which leaves some regions without solutions for end-of life wind turbine blades. It is likely that this is driving the limited and conservative blade recycling assumptions seen in some studies, including Heidak et al. (2025) where it is assumed that 90% of blade waste is going to landfills and 10% is being incinerated.

2.4.2.1.2 Knowledge gaps and recommended actions

Lund and Madsen (2024) conducted a systematic literature review examining value chains for end-of-life wind turbine blades. Their analysis highlights a significant imbalance in the existing research landscape. Most studies focus primarily on recycling technologies and the material properties of recovered blade composites, while comparatively little attention has been paid to the broader operational processes involved in managing blade waste. Crucially, none of their reviewed studies contained empirical data derived from real end-of-life blade projects. As a result, there remains a substantial lack of knowledge about the full value chain, including logistics, blade sectioning, pre-processing, and the refining of recovered materials for secondary applications. This gap also extends to understanding the environmental, social, and economic impacts associated with these processes.

The review further emphasises that uncertainty in the sector is compounded by the absence of reliable primary data and the diversity of potential logistics solutions across supply chains. The study cites the conclusions of Ratner et al. (2020) that there is great uncertainty in current estimates, both due to the lack of primary data and because of the variety of logistic solutions for supply chains. Moreover, the literature has not sufficiently addressed key contextual factors such as regional differences in infrastructure, legislative frameworks, transportation requirements, or technological readiness levels for different recycling options. Consequently, there is currently no clear consensus in the literature regarding the most appropriate end-of-life recycling technology for wind turbine blades. The study therefore highlights the importance of cross-sector partner collaborations to develop sustainable value chains.

Similarly, Beauson et al. (2022) identified several critical gaps in the knowledge base relating to wind turbine blade circularity. Their review categorises these gaps into six key areas (Table 7).

Table 7: Critical gaps in wind turbine blade circularity knowledge base

Wind turbine blade circularity area	Gaps to be addressed
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Assessment methods	Required to evaluate blade damage states and residual material properties, which would support decisions on reuse or repurposing.
Forecasting tools and models	Improvements needed to better estimate the timing and volume of blades reaching end-of-life.
Blade design approaches	Development of alternative materials or structural concepts to facilitate end-of-use processes.
Design of blades and recycling processes	Simultaneous design is needed to ensure strategies are integrated.
Recovered composite materials	Development of applications and market standards for recovered composites.
Life-cycle assessment (LCA)	Further studies are needed to evaluate turbine designs and recycling pathways to inform design guidelines and policy development.

Beyond research gaps, the study also identifies several needs from both industry and policy perspectives. From an industry standpoint, stakeholders require clearer decommissioning standards, including reference procedures for dismantling, transporting, and treating blades regardless of their residual economic value (Beauson et al., 2022). Guidance on designing blades for end-of-use considerations is also needed, alongside more reliable market forecasts for reuse pathways to enable better estimation of material flows and the development of viable business models.

From a policy perspective, improved traceability systems are necessary to support forecasting and evidence-based policymaking. Regulatory harmonisation for composite waste, the establishment of blade recycling standards, and guidelines for prioritising recycling solutions based on economic, environmental, and social impacts are also identified as key requirements for enabling a more sustainable wind turbine blade value chain (Beauson et al., 2022).

2.4.2.2 Other components end of use technology considerations

This section discusses a collection of insights about end of use technology considerations for other wind turbine components. Themes covered are component reuse practices, structural component end of use, critical material recycling, and using recycled materials in manufacturing.

2.4.2.2.1 Component reuse practices

References to component reuse in literature are limited, with only one paper reviewed providing valuable insights on this topic. Mendoza and Pigosso (2023) assessed the wind energy industry's readiness to transition toward a circular economy by examining the practices of three global wind turbine component manufacturers using the Ready2LOOP framework. The framework identifies strengths, gaps, and priority areas across eight business dimensions, highlighting opportunities for circular business models and providing guidelines to enhance resource efficiency and sustainability in wind technology systems. Their analysis focused on the extent to which circular strategies, such as repair, remanufacturing, and component take-back are already being implemented across key turbine subsystems. The findings suggest that several manufacturers have begun integrating circular economy principles into their operations, particularly through service-based models that extend the operational life of high-value components and reduce the need for new material production.

In the case of gearboxes, the study highlights that Siemens Gamesa Renewable Energy has implemented the OXiris program, which focuses on remanufacturing and re-engineering turbine gearboxes. The programme involves the disassembly and detailed inspection of used gearboxes, followed by the repair or replacement of damaged components. Both reused and new spare parts are utilised to restore the gearbox to OEM specifications. In addition to restoring functionality, the process may include design upgrades to improve performance and efficiency. According to the study, this remanufacturing approach can extend the lifespan of a gearbox by up to 60% while costing roughly 20% of the price of a new unit, demonstrating both economic and resource-efficiency benefits.

Circular solutions were also identified for minor components. The company HINE Group offers repair and upgrade programmes for wind turbine hydraulic units, including reverse engineering and retrofitting services. These activities enable the refurbishment of existing systems and the replacement or improvement of outdated components, thereby extending the operational lifetime of hydraulic equipment and reducing waste generation associated with premature replacement. Similarly, INGETEAM provides take-back systems for electronic components such as turbine control cards and offers services for reconditioning and repair. By collecting and refurbishing these components, the company enables their reintegration into operational systems, reducing the demand for new electronics and mitigating electronic waste. Collectively, these examples illustrate how circular economy strategies are already being applied within specific turbine component value chains, although their adoption remains uneven across the broader wind energy sector.

Insights from stakeholder interviews reinforce and expand upon these findings. Parts were described to be on offer either in a refurbished or "as-is" condition. The scale of the opportunity for refurbishment was described as being significant, with one stakeholder stating that up to 34,000 parts are known to be refurbishable, with coverage across major and minor components. Yaw gears were repeatedly raised as an example of components that are regularly used as refurbished parts. It was also noted that UK supply chain capabilities are increasing as more companies develop the knowledge and facilities required to refurbish parts.

A key mechanism supporting the circularity is the utilisation of service exchange agreements, whereby a functioning component is supplied to an asset operator in exchange for a worn or damaged unit, which is then refurbished and returned to stock for future use. It was noted that the uptake of refurbished parts for the repair of wind assets is variable. A market leading example referred to was an OEM that has publicly stated that more than 30% of the parts replaced in their service business (measured by weight) are refurbished, with targets to increase this to 55% by 2030. However, there will be asset owners in the market that will be operating significantly below this level, with stakeholders raising significant variability in willingness to consider refurbished parts and stating that the OEM's were in the best position to carry out repairs due to part knowledge.

Stakeholders discussed market drivers that incentivised the use of refurbished parts, these included lead times, cost and availability of new parts, and obsolescence.

“The decision making drivers are availability, so lead time and price...The other thing is really about access to the spare parts because we have several examples where the component is no longer manufactured, so you only can access new parts if you find them somewhere around the world. Otherwise, you have to go with the refurbished component.” EU Supply chain company

From the specific examples given by a small number of interviewees, there is good evidence to show that refurbished major and minor components are significantly cheaper (by 30-50%) than new equivalents.

2.4.2.2.2 Structural components end of use

Waldron et al. (2018) examine the technical feasibility of reusing onshore wind turbine foundations during repowering, focusing on structural fatigue limitations and soil–structure interaction for turbine sizes and reuse scenarios in the 0.85MW-5MW range. The study highlights key components such as the tower–slab connection and the main foundation slab are typically fatigue critical and designed for the original turbine lifespan. Because these areas experience high cyclic loading and stress concentrations, they rarely possess sufficient residual fatigue capacity to support an additional 25–30 years of operation. While remediation methods exist to address defects, they generally provide only limited life extension. The study also notes that although the existing foundation mass can theoretically contribute to resisting overturning forces, integrating it into new load paths through anchors is technically challenging and costly due to the high fatigue demands and installation requirements. Several reuse configurations are proposed, including constructing a new reinforced concrete slab over the existing foundation after removing the plinth, building a new slab above ground level while leaving most of the plinth in place, or constructing a new slab around the existing plinth using a complex steel transition piece. Each option involves trade-offs between demolition work, additional material requirements, and engineering complexity.

Stakeholder insights broadly align with these findings, with examples of remaining useful life assessments being carried out on the existing infrastructure to determine suitability for repowering. Reference was made to a site in Sweden where different turbines had been

installed on the original foundations using a modified transition piece. However, discussions on this topic were limited and site specific, therefore drawing conclusions on the viability of this option is not possible.

Instead, stakeholders described partial removal of foundations as being common practice, with site specific factors influencing the process, including local legislation, landowner agreements, and site restoration requirements (particularly for peat sites). Typical depth of removal at UK sites were quoted as ranging from 0.5-1 meters. This figure was shallower than typically quoted for projects decommissioned in Europe where foundation removal of 2 meters or more was typical.

Concrete processing was generally perceived as being well established with the material described as “eminently recyclable”. There are numerous companies capable of grinding or crushing the material enabling it’s reuse in concrete or as secondary fillers. Factors that were considered when processing the material were transport costs, with stakeholders describing using companies local to the decommissioning site.

Steel recovery and recycling, particularly from towers and offshore monopiles, is also viewed as a mature and effective process. Stakeholders reported that steel components achieve high levels of recyclability, with established supply chains in place to process and reclaim materials. However, despite interest in developing a more circular domestic system, much of the recovered steel is currently exported to Europe for smelting before being reimported into the UK as finished products. This highlights a missed opportunity for creating a closed-loop system within the UK wind sector. There is clear industry interest in improving circularity, particularly in retaining high-quality steel within the domestic supply chain. For example, offshore asset owners expressed interest in reprocessing steel from decommissioned monopiles and reusing it in future projects, reflecting the potential for high-grade material recovery to support new infrastructure. However, achieving this vision depends on both technical feasibility and supply chain development.

“I think an area of interest for us, whether or not it's viable for our earlier sites, is trying to create that circularity where we can bring our old monopile, which has got comparatively high-quality steel, bring that in, send that back to the steel mills. I'm not sure what process or anything they use, but essentially, good quality in means they get good quality back out, and the ideal would be to use our old sites in the foundations of our new sites and get that circularity even within our own organization.” Offshore asset owner

The main sources of the steel material from turbines include the towers and offshore wind monopiles. For towers, it was suggested that for all scenarios other than whole asset sale, the tower would likely be sold as scrap for material recovery. When discussing offshore monopile foundation removal, full monopile removal was indicated as the default requirement. However, questions were raised on the viability of achieving full monopile removal due to technical and financial challenges. References were made to ongoing research on this topic, with alternative

options being explored including cutting the monopiles, as seen for O&G infrastructure. The selected solution will impact the volume of steel recovered from monopiles.

2.4.2.2.3 Critical materials recycling

Friebe et al 2025 investigate technical approaches for recycling neodymium-based permanent magnets through the “magnet-to-magnet” recycling pathway. This method aims to directly recover magnetic materials from end-of-life products and reprocess them into new magnets. A critical step in this process is the grinding of neodymium-iron-boron (NdFeB) magnet material into very fine particles, typically below 5 µm, to produce a fine-grained neodymium alloy suitable for further metallurgical processing. Their experimental work demonstrates the feasibility of achieving these particle sizes when processing magnet material from hard disk drives, highlighting the importance of efficient grinding techniques in enabling closed-loop recycling of high-performance permanent magnets. Similarly, Gergorić et al 2019 examined hydrometallurgical methods for recovering REEs from NdFeB magnet powders. In their experimental study, magnet powders procured from the University of Birmingham were leached using aqua regia and analysed through inductively coupled plasma optical emission spectrometry. The research focuses on the leaching kinetics of these REE, as they represent the main target for recovery in recycling processes.

Despite the technical feasibility demonstrated in laboratory studies, recovery of REE from wind energy technologies remains limited in practice. According to Mendoza and Pigosso (2023), while most wind turbine components such as gearboxes, generators, and converters are metal-intensive and technically recyclable, the recovery of REE used in permanent magnets remains extremely low, estimated at only around 1–2% in the European Union. In addition, certain alloying elements used in turbine components, such as vanadium in gearboxes, present further challenges due to the technical complexity and high costs associated with their separation and recovery. These factors highlight the gap between laboratory-scale recycling research and the current industrial recovery of critical materials from wind energy systems.

2.4.3 Summary of potential for component reuse and material recovery

This section discussed the potential for component reuse and material recovery from existing wind assets, based on over 50 publications. The review covered material flow estimates and technologies for recovery, however turbine/component reuse was not widely studied.

Material flow estimates for wind turbines showed a decrease in material intensity over time. Studies from Germany and Denmark estimated significant material recycling potential, with steel, copper and REEs identified as key materials. However, the recycling of REEs remained limited due to high process costs. Onshore wind studies forecast that materials like steel and fiberglass will dominate the waste streams by 2050, with a significant proportion of turbines undergoing reuse. Offshore wind, with larger turbine capacities, is expected to significantly increase material demand, especially for steel, copper and REEs, by 2040. Recycling rates for offshore wind materials are projected to be modest, with scenarios showing that lifetime extension can help reduce material demand by around 7-8% for various metals and concrete.

The growing demand for materials, especially in offshore wind, will require innovative recycling solutions and extended turbine lifetimes to mitigate resource shortages.

Challenging material flows, focusing on turbine blade waste and critical materials from magnets, were also discussed. Global turbine blade waste could exceed 2 Mt by 2050, with estimates ranging up to 44 Mt. Insights from the US suggest an annual outflow of 5.3-10.5% of blades of the total fleet of blades that have reached the end of their technical design lifetime. Waste volumes vary significantly based on turbine lifespan. In Europe, blade waste is forecast to reach 325,000 tonnes per year by 2050. The UK, with 24,500 turbines, faces a rising waste stream as blades reach the end of their lifespan.

The reviewed literature indicates that the potential for meeting future neodymium demand in the wind sector through recycling and reuse remains highly constrained. Existing studies consistently report low recycling rates, typically below 1%, with upper-bound scenarios of 30–35% relying on highly optimistic scenarios. Even under scenarios with substantial technological advancements and recycling efficiencies, primary material demand is only partially offset due to the long operational lifetimes of wind infrastructure and the rapid scale-up of renewable energy systems. Evidence from global, US, and EU studies converges on the conclusion that recycling alone cannot mitigate supply risks for critical materials. While alternative strategies such as design improvements to reduce material intensity, substitution of critical materials, or direct reuse, are proposed, each faces technical, economic, and systemic limitations. Furthermore, empirical evidence highlights that current recycling practices often result in downcycling, particularly in the EU context, thereby limiting the recovery of high-value REE.

In contrast, the literature on end-of-life management of wind turbine blades is more extensive, with a strong focus on recycling technologies. Mechanical recycling is identified as the most technologically mature and environmentally favourable option, although it yields lower-value secondary materials. Thermal and chemical recycling methods demonstrate potential for higher-quality material recovery but remain constrained by cost, scalability, and technological readiness. Reuse and repurposing pathways have been shown to be technically viable; however, their implementation is limited by logistical challenges, variability in material condition, and the absence of standardised assessment methods. Across the value chain, significant knowledge gaps persist, particularly regarding real-world operational processes, supply chain logistics, and the environmental and economic performance of different end-of-life strategies. The lack of empirical data, harmonised standards, and supportive policy frameworks further contributes to uncertainty and limits large-scale deployment. Although emerging circular practices, such as component remanufacturing and refurbishment, demonstrate potential, their adoption remains fragmented, underscoring the need for coordinated research, industry collaboration, and policy development to enable a more circular wind energy system.

2.5 RQ 2b: Quantitative economic, technical, social and environmental values

This section presents the review findings regarding RQ 2b, assessing what the highest value use of recovered materials and components might be. It reviews quantifications and comparative assessments of economic, technical, social or environmental values of materials and components in wind under diverse scenarios.

Drawing on review results from over 40 publications, the literature revealed a number of themes including values of materials and components recovered from end-of-life turbines, including steel, composites, and REE with environmental values primarily focused on carbon (which will be covered in detail in Section 2.4)

Moreover, a number of themes came to the fore, that closely link to other sections in this review namely component failure rates (Section 2.1.2.1), LCA data from wind turbine operations phase (Section 2.3), cumulative material demand and volumes of materials from EoL wind and material composition of turbines (Section 2.4) and maintenance costs (section 2.6). These aspects have been moved to the respective sections instead. Finally, evidence on social values was limited to minor information on jobs (covered in Section 2.7) and community engagement.

2.5.1 Waste hierarchy and value retention

A number of methodologies were observed in the literature for decision-making in circular economy assessments and end-of-life management. The approach utilised in (Kramer et al., 2024) is the application of waste hierarchy principles, which utilises the “9R” strategies of waste hierarchy when conducting material flow modelling. Referring to the 9R-ladder by Potting et al. (2017). The R-principles rank decisions in order from higher to lower sustainability value: refuse (R0), rethink (R1), reduce (R2), reuse (R3), repair (R4), refurbishment (R5), remanufacturing (R6), repurposing (R7), material recycling (R8) and energy recovery (R9). Similar value retention hierarchies are discussed in Beauson et al. (2022) and Bennet et al. (2020), with references to narrowing, slowing, and closing the circularity loops that can be achieved via different EoL option. Jacobs (2025) developed a Multi Criteria Assessment (MCA) to guide the assessment of different EoL treatment options and inform a hierarchy of preference for future decommissioning practice. The prominent factors relating to decommissioning of Scottish onshore wind turbines were identified and categorised through an extensive literature review and market engagement. The MCA methodology was based upon circular economy principles identified in the ‘Making Things Last: A Circular Economy Strategy for Scotland’ (The Scottish Government, 2016) and also reinforced in the recently published ‘Circular Economy and Waste route map to 2030’ (The Scottish Government, 2024).

Evidence from stakeholder interviews indicates that real-world practices closely align with these hierarchical frameworks. Life extension is already being seen for UK onshore wind assets, with similar expectations for offshore wind. When a turbine is decommissioned, the process described for the resale of wind assets starts by investigating the opportunity for a

whole asset sale. Where sale of the whole turbine isn't possible, companies will begin exploring sales for the components within the turbine. For turbine models that are highly in demand, components may be stored until a sale can be secured. Any remaining material following this process will then be sent for material recovery, often where the turbine is not desirable due to obsolescence or damage. Early engagement when consulting on decommissioning projects was highlighted as critical to being able to maintain the assets at their highest values. With knowledge on the correct handling of components like gearboxes noted as being particularly important such as not to damage the assets. There is a consensus that for onshore assets, reuse of turbines is being increasingly considered as a desirable and realistic option for asset owners undertaking a decommissioning project. One of the key drivers for the sale of second-hand turbines includes rules and restrictions relating to turbine tip height in UK onshore wind consenting. As a result, the use of smaller turbines is necessitated, and yet turbine models of this scale aren't available for purchase as new from wind turbine OEMs. There was a comment on the potential for non-European OEM's to enter the market with offerings of smaller turbines, however this is not yet seen as current practice, with the purchase of a second-hand turbine being most commonly observed.

"You know what is happening in all of Europe actually is that a lot of project sites, they have a tip height restriction ... And [European OEM's] don't produce those turbines anymore. It's all bigger and higher. So for those developers who have a site or a permit ... they can choose between a second hand wind turbine or Chinese technology. And so far, we see that they are choosing the second-hand wind turbines", EU Supply chain company

Interviewees discussed the differing options with regards to the condition of the turbines. With market availability including turbines that have been fully refurbished prior to resale, whilst others are offered on a "sold as seen" basis. Whole asset resale was described as being quite common, with numerous examples provided of the practice in Europe. There was also an example provided of refurbished turbines being sold into Northern Ireland, with the UK market described as being promising for the sale of whole second-hand assets.

"Last year Sweden was a big market, but this year the UK market will be our main focus because we see now with the change of regulations that demand is growing again and we have some nice projects coming up." EU supply chain company

It was generally commented that the UK has not seen many onshore decommissioning projects, which may be influencing the observed flows of whole turbine assets. Nevertheless, one asset owner discussed interest from UK stakeholders in obtaining assets that are due to be decommissioned, which suggests that this will become a stronger trend as decommissioning activity in the UK increases.

Asset owners and decommissioning companies described their sales process and hierarchy, with a strong preference for the sale of whole assets where possible. Examples were provided of the sales process beginning up to 9 months ahead of the date of decommissioning, with

early consultation increasing the likelihood of the assets being retained in their highest value state. However, it was noted that the ability to sell whole assets is highly dependent on the model and condition of the turbine.

Market dynamics also play an important role. Participants indicated that some turbine types have a good reputation and strong resale value. Other turbine models are less sought after and not sold as whole turbines. Some participants described typical ranges for turbine resale:

“I would say that for example, if you're decommissioning a wind farm with 10 turbines, it's going to be very difficult that you are able to sell all the 10 turbines as a whole. So, what is happening there is that we are successful in selling maybe one or two turbines to one customer or two different customers. If that option is not possible, so if you're not able to sell the complete wind turbine, then we go to the main components...but it depends a lot on the turbine type, whether you have a market for the main components or not.” EU supply chain company

“I think on average we decommissioned 30 turbines this year...of the 30 turbines at least 20 turbines are reinstalled” EU Supply chain company

It is worth noting that in the higher end of these cases, stakeholders have been specifically targeting assets decommissioned within the age range of 20-25 years and are therefore more likely to be suited to a second life. The availability of these turbines has been driven by favourable onshore repowering policies encouraging early decommissioning, including repowering subsidies in France.

A challenge raised with regards to the resale of assets was the requirement for aligning timelines with a suitable off taker, as the costs associated with storage, transport, and craneage impact the economics of whole asset sales. Looking to the future, it was mentioned that the costs of decommissioning and transporting larger turbines may shift the economics of reuse, resulting in a preference for alternative strategies.

Information on offshore practice was more limited, stakeholders mentioned not being aware of any offshore turbines currently being traded on the market. This was attributed to the assets being relatively young when compared to onshore wind, and therefore not yet being decommissioned at any great scale. Where stakeholders were able to discuss historic offshore wind decommissioning projects, they stated that the assets had gone into material recovery streams rather than being sold as whole. One stakeholder stated that their expectation is that offshore assets will be run to their technical EoL, resulting in the turbines being unsuitable for a second life as a whole asset, whilst an asset owner stated that they had not ruled out the option for whole turbine resale but were struggling to identify a suitable market. Therefore, at this stage the information provided by stakeholders on the potential reuse of offshore turbines is too limited to draw any clear conclusions.

Where whole asset resale was not possible, stakeholders indicated that the next option explored was the recovery and resale of components or “parts” as the next best value recovery option. Asset owners described firstly looking to their own operating fleet to identify any

opportunities for cannibalisation of the decommissioned assets to build an inventory of spare parts, reducing exposure to supply chain bottle necks and delays. Where suitable opportunities within the asset owner's own fleet aren't available, they stated they would then look at alternative buyers for the parts or components, with key customers including OEM's and service contract providers.

"If [reuse of whole turbine] is not an option, and it's often not, then we look at how we break down the turbine and how we can use the parts ... So, one of the first questions that we ask is can we retain anything from this turbine that is useful for us. And that's very interesting when you have a portfolio of ageing assets where turbine parts might be quite difficult to come by. And so when you are dismantling and decommissioning a project, what we will do is we'll assess whether or not we ... require any of these spare parts. So that would help us to build an inventory of spare parts that may help us reduce lead times and at procurement costs elsewhere in another project. So that's how we utilise the parts ourselves. If we don't need the parts, then we'll look to valorise the parts, so can we sell these parts and components as whole components potentially to other buyers in the second hand market", Onshore asset owner

As in the whole turbine case, the opportunities for component resale are linked with the turbine model type and condition, with some of the less in demand models seeing as little as 5% resale of components by turbine mass, with the remainder sent for material recovery.

Whilst decommissioning was described as a growing source of second-hand parts, currently the majority of parts available on the market are coming from operational fleets, with one spare parts supplier stating that up to 90% of the used components they offer are recovered during the turbine operational phase. This is an important consideration for modelling material flows. Stakeholders discussed both onshore and offshore wind being represented in the component reuse market. Onshore was discussed as the more mature market, nevertheless, supply chain companies discussed the upscaling of their operations to support the offshore wind industry.

"One thing that we have to consider is that, if you think about a complete wind turbine the components that are installed, they can be either new or refurbished. So, when a component breaks and it can be repaired, what can happen is that it goes to a workshop then it is put back on stock because the operator then takes one unit from stock, puts it in the turbine and that's how the material flows go. So a lot of times we do get access to refurbished parts ... or used parts that are not coming from decommissioned turbines, but that are coming from these second hand market that exists while the turbine is in its normal operation". EU Supply chain company

2.5.2 Economic value

2.5.2.1 Values of recovered materials and components

There is very limited evidence on the values of materials recovered from end-of-life turbines published in the literature base.

Jacobs (2025) find that when considering decisions at a component level, the optimal pathway was determined to be decommissioning and refurbish all components (apart from blades) for use elsewhere, followed by a preference for lifetime extension. The output scores for refurbishment and reuse were close, which demonstrates the interconnected nature of the solutions, as refurbished parts are often required for life extension. This means that it is difficult to draw firm conclusions on the two treatment options, as further calculations of GVA to include value added beyond decommissioning and initial treatment could result in the ranking order of these two options being reversed.

It is generally accepted there will be a significant positive value associated with “scrap” metal recycling of turbine structures and components but there are few values available in the literature to substantiate this. Two studies give values for the revenues obtained from metal recycling, ranging from £8,000/MW (Topham et al., 2019) for an offshore wind turbine, to £43,000/2MW i.e. (£21,500/MW onshore turbine based on steel alone (Jacobs, 2023).

In contrast, wind turbine blades receive more attention and are consistently characterised as representing a substantial negative value for asset owners, particularly if they are recycled or sent for waste disposal. Blades retain more value through lifetime extension while, in the absence of recertification schemes for blades, refurbishment is seen as high risk due to costs possibly outweighing potential savings (Jacobs, 2025). Whilst no sources record gate fees or costs for blade recycling options, there is some information on the drivers and economic viability of different blade recycling methods. Yu et al. (2025) note that fibre-reinforced polymer recycling is primarily influenced by the cost of the shredding process, with the particle size significantly determining the performance and application of recycled products. Some comments are provided on the value difference between virgin inputs and recovered materials from blades. Oliveux et al. (2015) note the value of recycled resin is 50% of that of virgin resin. For carbon fibres, the difference is even more stark, with recovered fibres approximately \$5/kg (£3.70/kg) compared to the virgin price of \$33/kg (£24.60/kg) (Yu et al., 2025). In their study, Liu et al. (2022) utilise a crude estimation that the value of the recycled fibre is assumed to be proportional to its tensile strength. For example if the strength of the recycled fibre is 80% of virgin fibre, then its value is 80% of virgin fibre.

Despite these barriers, scenario modelling by Ghosh et al. (2022) found that that low and moderate circularity costs resulted in essentially the same circularity transition, and this finding implies circularity processing costs may not be a major obstacle to a wind turbine blade supply chain transitioning toward circularity. Similarly, Lund and Madsen (2024) note that the first end-of-life processing steps for the recycling of turbine blades are similar, regardless of recycling technology choice.

Another material that was covered in the literature was REE. The literature was not always directly related to the wind industry, nevertheless useful insight on costs and market drivers could be obtained. Patil et al. (2022) observes that the prices of REEs are entirely determined by suppliers and manufacturers. Prices for REEs (Nd, Dy, and Tb) have been increasing since mid-2020 – at time of writing, Tb is \$1450/kg. Pricing fluctuations are due to supply monopoly and additional dumping of some of the abundant REEs such as La and Ce. The profitability of REE recycling mostly depends on the prices of the elements to accommodate the processing costs. Therefore, EoL REE recycling should focus on the most valuable and critical REEs. Targeting recovery of the most sought metals such as neodymium (Nd) can help avoid the overproduction and uneven pricing of low-value metals such as lanthanum (La) and cerium (Ce). An industrial recycling plant for REE magnets requires 1000 ton magnet/year and is not expected before 2033, especially as wind turbines are being designed for a service life of 20 years. REE magnets are typically not included or defined in cost evaluations of materials yield from end-of-life wind turbines. In a separate examination, Brião et al. (2022) concluded that direct reuse of REE magnets from wind turbines and large electric generators is the most economical and environmentally viable EoL option. This is due to the relative benefits versus recycling, namely the low energy cost, the absence of chemical reagents' consumption, and the non-generation of waste. However, Meng et al. (2025) report barriers to direct reuse and argue that recycling will generally be the more likely end-of-life pathway

Insights from stakeholder interviews reinforce many of these findings while highlighting additional real-world constraints. In practice, asset value is typically realised through a clear hierarchy: prioritising life extension, followed by whole turbine resale, component reuse, and finally material recycling. However, valuation approaches are often conservative. It was described as common practice for a decommissioning company to pay scrap or near-scrap value for an “as-seen” asset, with anything that can be sold at a higher value being seen as a bonus. This conservative approach is driven by a lack of supplied information, which increases the risks associated with taking on the asset. This lack of information was also highlighted as being a challenge for valuating key materials such as REE magnets, as the exact composition of the materials are unknown. The market was described as being in its infancy and therefore knowledge is still being gathered on the components and materials that are becoming available. Stakeholders described the significant time investment required to understand the potential downstream market which may include the use of some components in industries outside of wind.

“Decommissioning companies, if they are taking over the asset, they just have a weight for the complete turbine and they just put a number next to the euros per kilo...assuming that everything needs to be recycled ... and the recycling companies will pay the steel value and then everything that can be sold in a higher value, so refurbished or repurposed or whatever, then it's going to be a plus. But I think from what I've seen, it's a very conservative approach because access to information is very scarce”, EU Supply chain company

Finally, the absence of standardisation and consistent quality assurance frameworks presents an additional barrier to value realisation. Stakeholders discussed the variability in quality of

repaired and refurbished parts, with some areas of the supply chain described as a “wild west”, resulting in an increased perception of risk by asset owners. It was also noted that harmonisation of the information shared when parts are sold would be beneficial when attempting to attribute value to the components. Current data provisions are highly variable, with some parts having no provenance whilst others are provided with an overwhelming level of detail, of which only a fraction is relevant. References were made to other industries, particularly aerospace, where there is greater traceability of parts and clear quality requirements for refurbished parts. There was appetite shown for professionalising the industry and raising the bar collectively.

2.5.3 Social values

Evidence on social impacts and benefits form a clear evidence gap, with very limited results available. Some minor results refer to community benefits (such as ZWS, 2024). However, most social benefits that are reported pertain to job creation, which will be covered in Section 2.7.

2.5.4 Environmental values

Overall, lifetime extension is expected to save materials and GHG emissions (see section 2.3). However, locally there could be more emissions and environmental impacts such as transport noise. It should be said though, that current understanding of offshore wind decommissioning is limited (Stravens, 2025).

Further results are heavily skewed towards LCAs and assessments that compare the environmental impacts of blade treatment options. It is largely agreed that landfilling is the least favourable option for blades from an environmental perspective. This is further explored by Nagle et al. (2020) who found that increasing material substitution rates in the cement production process has a greater beneficial impact than reducing transportation distances, such that export for co-processing was markedly beneficial in comparison to domestic landfilling.

The reported energy demand of blade recycling techniques varies widely. Mechanical processes have been reported to have the lowest energy demand, while solvolysis techniques span the largest range, reaching the highest energy demand. This is due to the high temperatures, and sometimes high-pressure equipment, needed to perform solvolysis (Bennet et al., 2020).

Environmental impact is also examined in comparison to the product or power being substituted by blade treatment. Cong et al. (2023) reported that the disposal of blades via incineration for electricity, co-processing, producing concrete by EoL blades instead of aggregates, and producing concrete by EoL blades instead of cements all have a lower carbon impact than conventional electricity generation, cement clinker production and concrete production respectively.

Several studies note challenges around changing composition of blades and that this is a crucial factor in assessing the long-term environmental impact of recycling strategies. This may be especially relevant on carbon fibres, because the production of carbon fibres originating from virgin materials is a relatively high-energy consumption process (198–595 MJ/kg) that generates significant pollution, when compared with carbon fibre recovery (Yu et al., 2025). With that in mind, Pender et al. (2024) suggest that recycling solutions that go beyond mechanical recycling will be particularly important from 2040 onwards, when a greater proportion of blades with mixed glass and carbon fibres may enter the waste stream, to minimise the overall carbon impact of the chosen process.

The environmental impact of other materials receives less coverage. Amato et al. (2019) pointed out that secondary neodymium productions from permanent magnets can reduce carbon emissions by 6 times and 7.1 times the production cost compared to primary production (see Section 2.4 for detailed results on REE and magnets).

2.5.5 Summary of economic, technical, social and environmental values

Across the literature and stakeholder evidence, higher-order circular strategies consistently deliver higher value than lower-order options. Lifetime extension, whole-turbine reuse, and component reuse or refurbishment retain functional integrity and embedded value and therefore outperform material recycling across economic and environmental dimensions where technically feasible. Material recycling, particularly of metals such as steel and copper, delivers positive but lower value by recovering material rather than function, while downcycling (e.g. concrete crushing or composite recycling) provides limited value retention. Disposal and landfill represent the lowest-value outcomes.

The evidence base is strongest for economic and environmental values, where refurbishment, reuse and metal recycling show clear advantages. In contrast, blade treatment options generally exhibit low or negative economic value under current conditions, despite offering environmental benefits relative to landfill. Social value remains weakly evidenced, with limited data beyond indicative employment effects addressed under RQ 3b. Across all dimensions, value outcomes are highly sensitive to asset condition, component demand, logistics, and the availability of standards and quality assurance for reused or refurbished parts.

2.6 RQ 3a: Economic impacts of repair and recycling

The topic of economic impacts of repair and recovery activities was reasonably well addressed, with 25 pieces of the reviewed literature providing some discussion on the topic. However, the insights provided in this category were relatively varied with areas addressed covering O&M, EoL disposal, and material processing costs. Therefore, there are limited areas where unified consensus can be drawn.

2.6.1 UK supply chain economic opportunities

The emerging UK supply chain for component refurbishment was noted by interview stakeholders as a growing area of success, with multiple companies offering specialised engineering expertise. Some companies were wind-specific, whereas others had expanded into renewables having been established to service other sectors (e.g., O&G, food and drink, pharmaceuticals). Examples were given of smaller companies partnering with larger asset owners, particularly relating to reverse engineering and obsolescence of parts.

These supply chain companies discussed deliberately not trying to expand services too far outside of their specialism or compete with OEMs to ensure high quality and reliable offerings. Flexibility was seen as important to be able to adapt to changing demand and being able to problem-solve as issues arise for asset owners or operators.

“What we want, what we’ve tried to avoid is that one stop shop supply chain. We’re not in the industry for oil and greases or bearings, that type of stuff. We still want to stay quite niche. So, it’s partnerships where we can be aligned with what we’re already doing.” UK refurbishment company

Components that are currently being refurbished within the UK include gearboxes, generators, main shafts, braking systems, and yaw gears, with asset owners describing good relationships with the Small and Medium-sized Enterprise’s (SME) operating in this space.

Key opportunities were highlighted where the UK has strong expertise in other sectors that are transferrable to supporting the wind industry, with electronic components, control systems, power electronics, and motors highlighted as areas of growth potential.

2.6.2 Economic risks and concerns

One of the key concerns stated by interviewees was that the UK supply chain is not yet at a sufficient scale to meet the volumes needed to maintain aging turbines and to process decommissioning projects, with an uneven capacity across UK regions. This applies both to companies involved in refurbishment activity but also the waste and resources sector. Clear messaging emerged that for investment in diversifying and increasing scale capability, UK supply chain companies require certainty of pipeline commitments and early engagement from asset owners.

“...we looked at investing money to be able to [refurbish] main shafts, but there was no commitment from any owner or owner operator to use that service. It was a significant investment we needed, so cranes, redo foundations, and we would need to do about between 12 and 15 main shafts a year to make that commercially viable for us.” UK refurbishment company

For component refurbishment activity, this was viewed as a missed economic opportunity, with a significant volume of major components still being exported to the EU for refurbishment by partner companies.

Stakeholders noted higher barriers to entry for offshore components in contrast to onshore, including the need for accreditations and bigger tooling or plant. Where existing infrastructure does exist, it often doesn't have the capacity to handle the size and scale of offshore wind components. It is notable that even relatively large supply chain companies stated that they are unlikely to have the correct type of operational capacity to service the offshore wind industry without significant planning and investment. Similarly to onshore equivalents, this currently leads to offshore components being exported to the EU for refurbishment, rather than activity being carried out in the UK.

Forward-planning and strategic industry investment was highlighted as being particularly relevant for material recovery companies involved in decommissioning. Interviewees outlined challenges relating to the lack of domestic capacity for the forecasted upcoming projects.

"...we have a bit of a worry that ... people think, well the supply chain will just appear and it will handle this. You know it needs a bit of pre-planning and thought about logistics, space, downsizing markets because you would only need a couple of projects to actually come through at the same time and with current configurations you'd be full." Waste and resources company

"... we need that pipeline of what's coming and we probably do need more support from government on just building up that supply chain but also recognizing where the limitations are within the UK, what's possible within the UK, what can we do or where do we need partners, for instance in the EU." Trade body

The limited ability to move materials in and out of the UK was raised as an issue by multiple stakeholders, both in terms of material handling and sourcing of components:

"One of the issues we found in the UK particularly is around Brexit, getting parts exported, then imported again just takes such a long time and the hold-up at ports really means that the UK doesn't really benefit of the same refurbishment cycle as a lot of the European sites do, because a lot of our refurbishment centres are in Europe." OEM O&M company

One additional consideration emerging in Europe was the varying professionalism of decommissioning companies, with risks to the reputation of the industry and the public support for circularity due to rogue actors.

2.6.3 Operations and maintenance costs

One topic that was extensively discussed across multiple articles was the difference in O&M costs between onshore and offshore wind. Mishnaevsky et al. (2022) stated that the maintenance costs are 2 to 3 times higher for offshore wind turbines than for onshore wind turbines, a figure which is in good agreement with Peng et al. (2023) who states that offshore wind turbines cost about three times as much to run as their onshore counterparts.

Peng et al. (2023) review available literature for O&M costs as a percentage of the total Life Cycle Costs. O&M costs of onshore wind turbines can be as much as 10%-20% of the total electricity produced and as much as 20%-25% of the total electricity produced by offshore wind turbines. The O&M cost for offshore wind farms can account for around 40% of the total life-cycle cost of the project. Shafiee et al. (2019) discusses values for O&M costs for onshore wind farms comprising 5%-10% of the cost of energy while it is estimated to be between 20%-35% in offshore wind projects. Oh et al. (2024) quotes that throughout the entire life cycle of a wind turbine system, O&M account for 25–30% of total expenses. Meanwhile (Sathyan, 2023) states that maintenance costs represent 10%-15% and 20%-25% of the overall cost for onshore and offshore wind turbines, where the cost of unscheduled maintenance is about 30%-60% of the total. The numbers quoted in literature are reasonably well aligned, however the literature reviewed are predominantly review papers and therefore do not provide their own empirical evidence. In some cases, the original source papers are from the early 2010's (Sathyan, 2023; Oh et al., 2024). Therefore considerations should be made on the sensitivity of the models to O&M costs, and further interrogation of these assumptions via stakeholder interviews would be beneficial.

Building on the findings of relatively substantial life cycle O&M costs, there are a handful of papers that explore areas where cost savings can be made. Turnbull et al. (2021) estimates between 2% and 12.5% of costs can be saved by repairing a component early before major replacement is required. Compared to the baseline case this equates to a saving of approximately £0.355–£2.128 per MWhr over the lifetime of the wind farm. With regards to changes in lost production, between 3.6% and 15.75% less energy is lost across the range of simulations. Comparing predictive and condition-based strategies in more detail, results suggest that with a condition-based approach that utilises as much component life as possible before repair, an extra 1%–2% can be saved on average direct O&M costs. This equates to approximately £0.177–£0.355 per MWh over the lifetime of the wind farm. Results indicate that up to 8% of direct O&M costs can be saved through early intervention along with up to 11% reduction in lost production, assuming 25% of major failures of the generator and gearbox can be diagnosed through advanced monitoring and repaired before major replacement is required. This has the potential to be significant as Lam et al. (2021) suggests that gearbox operational costs account for 6% of the total maintenance costs of a wind turbine. Oh et al. (2024) also states that over a 20-year period, downtime for a 500 MW offshore wind farm can result in production losses of approximately 12 million euros per year.

Similarly, Shafiee et al. (2019) discusses how the O&M costs of a wind turbine over its operational life can be controlled through conducting preventive maintenance (PM) actions. To this aim, scheduled preventative maintenance actions are carried out during the constant failure rate period (typically between fifth year and fifteenth year of operation) to prolong the useful lifetime as well as over the wear-out period (usually after the fifteenth year of operation) to reduce the degradation rate. Even though overhauling may be a possible solution for highly reliable wind turbines, it cannot be considered as a long-term approach for maintaining the wind farms with high rate of failure. The article provides an example case of predictive maintenance for Horns Rev (also known as Horns Reef) offshore wind farm in the east coast of the North Sea which undergoes PM2 program. First, a minor PM task is carried out during

January and then a major PM is performed during the summer. The minor PM task usually takes two days and it costs about €1000 for each wind turbine, whereas the major PM takes three days and it costs roughly around €1500 per wind turbine.

2.6.4 Lifetime extension and repowering considerations

Tota-Maharaj et al. (2021) explores how extending turbine life through repair or partial repowering is generally cheaper than full replacement, because foundations and towers (the most material-intensive parts) are retained. Operators can continue generating income from existing assets without the large upfront capital cost of new turbines. There is potential for a secondary market for refurbished parts and turbines, which could create new revenue streams and reduce waste. Since there is an established market for steel and copper, recovery can offset some costs of the partial component removal. However, blade recycling is expensive and currently offers low economic return, making it less attractive without policy incentives. Transporting large components for recycling or remanufacture adds significant cost, especially for offshore turbines.

However not all life extension is more cost effective than repowering; Waldron et al. (2018) concluded that, for a specific wind site in Scotland, the reengineering cost per foundation is between 2 and 3 times more than a new foundation for the target turbine model. This translates into hundreds of thousands of pounds per foundation and would therefore represent a multi-million increase in cost for a typical >50 MW wind farm. Typically, the increase in cost is driven by the addition of mass concrete to form a suitable formation and by the fact that the reengineered foundation is significantly larger than a new foundation. The use of anchors does reduce the volume of the foundation. However, this is not a significant enough reduction to justify the additional cost of the anchors.

A few articles focus on industry level economic insights. For example, Zavvar et al. (2025) discuss the driving factors that influence asset management decision making, where the financial life extension depends on the balance between increased O&M costs due to aging assets and the additional revenue generated from extended operations. If partial repowering is employed without guaranteed Contracts for Difference (CfD) strike prices, operators face uncertain returns, increasing the cost of capital and reducing the likelihood of achieving suitable returns. Decommissioning is considered purely as a costly option with no return on investment, unlike lifetime extension or repowering, which generate revenue.

Sheiati et al. (2025) highlights a significant increase in OEM budgets for maintaining and repairing wind turbines, with Siemens Gamesa's warranty provisions increasing from €250 million to €650 million, and Vestas's provisions growing from €300 million to €815 million between the years 2019 to 2023. A proportional increase in warranty provisions as a percentage of revenue is provided, with Siemens Gamesa increasing from 2% to 4.5%, and Vestas's rising from 2.5% to 5.6%.

Everoze (2024) estimate the management of Major Component Exchange (MCE) as a £363 million opportunity for the UK; however, they note that it is an area of significant uncertainty for the floating wind sector, with three broad options in terms of the operations (tow to port, use

Heavy Lift Vessel or use of novel up tower crane solution). Jacobs (2025) states that the refurbishment of full turbine and reuse of components in a different turbine assumes a positive value generation of USD \$150,000 per MW (£107,885 per MW), while Zero Waste Scotland (2024) argued the principle that refurbishment is more profitable than recycling and, in turn, that recycling is more profitable than landfill. Material recovery generates value mainly through scrap metal recycling (the bulk of which is steel, to be exported).

Some articles focused on the economic costs and opportunities relating to wind turbine blades. A single structural blade repair by attaching a patch/scarf to the laminate, can take ca. 21 hours in technicians work with a cost of €4,800 when carried out at a wind farm; which is significantly cheaper than repair with transport of the blade to a factory (Mishnaevsky, 2021).

Liu et al. (2022) explored life extension costs and concluded that by summing up the material cost, transportation cost and labour cost, the annual total cost for life extension is calculated as \$68,957 for a 50 MW wind farm. Total costs for 2, 5, and 10-years' life extension are thus \$138k, \$345k and \$690k, respectively. Each 750 kW turbine blade weighs 2.9 tonnes (Zhang, 2016). A 50 MW wind farm has 66 turbines. Each turbine consists of 3 blades, therefore there are 398 blades in total. Total blade weight is 574.2 t. Therefore, the average cost for 5 years' life extension is \$60/t. If the maintenance and repair demand (repair frequency) of large blades remains the same as for small blades, material usage will increase and the reparation work will be more time consuming, but the inspection and maintenance workloads should not change significantly since this mainly depends on the number of blades. It is likely, therefore, that labour and transportation may not increase proportionally to weight and hence we assume that while material cost increases in proportion to blade size (a 4.31-fold increase in this case), the labour and transportation costs increase by a fixed 20% for large blade. After this calculation, the life extension cost of a large blade reduces to \$191/t, which is 69% lower than that of a small blade. The equivalent unit recycle value is the same as 750 kW lifetime extension for 5 years which is \$803/t. In this case, the net profit for lifetime extension is more than \$600/t which is triple then what was estimated for the base case (750 kW blade). Hence for the cost estimation on lifetime extension, blade size should be borne in mind.

2.6.5 Blade material recovery

Hasheminezhad et al. (2024) reviewed available literature on the disassembly and transport costs associated with wind turbine blades. The review found that disassembly, water jets, and contracting with a sawing service might cost approximately \$2200 per day. Assuming that each blade weighs 7 tonnes, it is typically possible to process 14 tonnes of blades daily, allowing for the disassembly of two blades per day. Hence the transportation of these segmented blades can be priced at \$660 each. It is important to note that transporting an entire uncut blade requires a special oversized transport, dramatically increasing the cost to about \$33,000. If the blades are destined for landfill disposal, they require further shredding, leading to fees of as much as \$220 per ton, along with a landfill waste acceptance charge of \$90 per ton (with higher costs possible depending on country). Blade treatment costs are not recorded for any treatment route other than landfill, which varies by country. Some studies report costs of \$90 per ton in the US (Cooperman et al., 2021; Hasheminezhad et al., 2024), whilst Beauson et al.

(2022) observed fees of around €120-145 per tonne in the UK and Denmark (and note that composites are banned from landfills in Germany). Two studies demonstrate that larger pieces of blade cost more to dispose of in landfill than shredded material, further demonstrating the interplay between processing costs and disposal fees (Cooperman et al., 2021; Hasheminezhad et al., 2024).

On the other hand, if blade reuse is viable, it is essential to first determine what percentage of the blade material is reusable. The paper provided an example from Pronk (2022) which suggested that 40% of a General Electric 37m blade can be reused and sold as structural elements in construction. The associated costs for this process, including scanning, sawing, and storage, are calculated to be approximately \$715 per ton. The unusable parts of wind turbine blades could be considered as input material for cement production with a cost of about \$560 per ton. This process included \$170 for further segmenting the blades into pieces of suitable size and an additional \$390 for the transportation of these pieces to the cement company.

These sources are substantially higher than the value used in the modelling of Liu et al. (2019) which attributes a value of \$40 per tonne (approximately £30 per tonne) against cutting and dismantling of blades, which looks to be a significant underestimate. Such variations can possibly be explained by geographic location factors such as costs of labour, manufacturing and energy (Liu et al., 2022).

Another summarised example from Cooperman et al. (2021) similarly compared disposal costs for blades from three different-sized wind turbines in the U.S. It was found that most of the cost is associated with blade disassembly which increased with blade size. For example, costs for dismantling 750 kW and 2.5 MW turbine blades were approximately \$18/kW and \$30/kW, respectively. Because disposal fees at landfills known as tip fees are calculated either by weight for small shredded pieces (1–3 cm) or by volume for larger segments (30 m), two different cutting approaches were analysed. While the tip fee for blades shredded into small pieces was fairly consistent across all sizes, the fee for a 2.5 MW blade cut into large segments was nearly double that for a 750 kW one. Overall, it was estimated that end-of-life cost per turbine could range from about \$5,000 to \$33,000 for each blade of the three turbine sizes studied. For example, while decommissioning costs can be as much as \$75,000 per turbine in some areas, in New South Wales, Australia, it might be approximately \$12,450 after factoring in salvage value (Sakellariou, 2018). The literature for blade recycling is very comprehensive, and makes up a relatively small part of the overall research focus, therefore it is proposed that the values that have been obtained from literature should be sufficient for the modelling work in phase 3.

2.6.6 Decommissioning costs

There is a small evidence base for decommissioning costs. These are either given per turbine or per capacity basis, which must be noted when drawing comparisons.

There is broad agreement between two studies looking at onshore turbines in the US, with a range of \$25,000-75,000 (£18,600-55,900) per turbine (Sakellariou, 2018) falling in line with

the \$26,000 (ca. £19,300) per MW with a hub height of 80m, with an adjustment of $\pm$ \$4,000 (ca. £3,000) per MW for each meter of hub height above or below 80m (Eberle et al., 2019). These US figures are substantially lower than UK estimates.

One study from the UK puts these onshore figures in a higher range of £34,577 per MW in the UK (Jacobs, 2023). However, this study notes that this figure is based on data from 2012 and that there is a significant data gap in this area, with some industry feedback and more recent examples citing decommissioning costs at around double or triple this figure per MW. Decommissioning costs for offshore wind farms are likely to be much higher, with one estimate from Topham and McMillan (2017) putting the figure at around £200,000 per MW.

A study from Zero Waste Scotland (2024) demonstrates the added value of going beyond decommissioning and instead incorporating lifetime extension and repowering with insights from the Hagshaw Energy Cluster. The cluster has 584 MW committed and is aiming for a total of 1GW output. From the seven wind farms with over a hundred turbines, there are currently four consented with over fifty turbines, from new, lifetime extension and repowering schemes. This is associated with £525M capital investment and £18M operational expenditure. Despite the inclusion of a £1.7M budget for community benefits (assuming this is a one-off budget), communities do not feel engaged. One of the connecting hubs aims to integrate circular economy, associated with a further £17.7M investment and creating 80-100 jobs.

Stakeholder interviews provide further context and reinforce the variability in decommissioning costs. Estimates for onshore wind decommissioning gathered from stakeholders with project experience in the EU varied from €50k (£39k) for a 600kW turbine to €100k-150k (£86k-129k) for a 2MW turbine. Figures were given as net costs including foundation removal and positive value from scrap metal sales, but exclusive of blade management or waste treatment, which has a significant impact on the overall cost.

Decommissioning costs for offshore are even more uncertain, due to the varying scope of anticipated works (e.g., foundation removal versus left in-situ) and lack of practical experience globally. One stakeholder stated that a net cost to the asset owner of £1M per MW would be a conservative estimate, but with a high level of uncertainty on this figure.

“We have some underlying standard assumptions, it is very site specific and the models are untried, untested, and they take normally a bit more of a top-down approach. Until we actually get into the throes of building a [decommissioning] project, executing a project, taking all those lessons learned, and having the corresponding bottom up costings and risks and contingencies and all that good stuff, it's really difficult to get a feel for how much it will cost in the future.”
Offshore asset owner

2.6.7 Summary of economic impacts of repair and recycling

The review of economic impacts of repair and recovery activities in wind turbine operations covered the topics O&M costs and lifetime extension, repowering, and end-of-use disposal. The variation in the findings made it challenging to establish a consensus.

The literature extensively compares O&M costs for onshore vs. offshore wind turbines, with offshore turbines generally being 2-3 times more expensive to maintain. O&M can account for 10-25% of the total electricity produced by onshore and offshore wind turbines. PM and early repairs are identified as strategies for reducing these costs. Early component repairs can save 2%-12.5% of costs, with a reduction in lost production. Condition-based maintenance can further save up to 8% of direct O&M costs. For instance, gearbox operational costs represent about 6% of maintenance costs, and downtime in offshore wind farms can result in substantial annual production losses.

Repairing or partially repowering wind turbines is generally cheaper than full replacement. However, the reengineering costs for foundations can be significantly higher than new installations, especially when anchors are used. A secondary market for refurbished parts has started to create new revenue streams.

Despite research progress, blade recycling remains economically challenging without policy incentives, with significant costs looming for blade end of use management. Transporting blades for recycling, particularly large offshore ones, can be extremely costly. Reusing materials, such as in construction, offers some economic benefits. Additionally, REEs have volatile prices, affecting the profitability of recycling alongside the technical challenges.

2.7 RQ 3b: Employment impacts

Three themes emanated from the literature, namely jobs impact of increasing levels of repair and recovery from wind turbines, job projections for O&M sectors in both onshore and offshore wind, and jobs associated with material outflows from EoL wind.

There is very limited coverage in the literature of the impacts on jobs of repair and recovery activities. Only seven publications make any reference to this topic, and it is notable that five of these are grey literature sources. Only two of these studies make any significant attempt at analysing the Full Time Equivalent (FTE) impact of repair and recovery activities as ringfenced activities.

Despite this, some indicative insights can be drawn. BGV Associates (2023) examined the potential market that would be driven by refurbishing ten common major and minor components from operational wind farms in the UK. They found that this would generate an estimated potential UK economic impact of 2,209 FTE in 2025, increasing to 3,581 FTE in 2035 (the total of direct, indirect, and induced FTEs). However, this study did not include turbine blades or decommissioning operations.

Bennet et al. (2020) suggested that a circular economy for wind could create additional jobs. If the focus would be on recycling primarily, then a further 5,000 jobs could be created in the UK. Adding more advanced circular economy approaches such as reuse, refurbishment and especially remanufacturing could see an expansion to 20,000 jobs by 2030.

There has been some examination of jobs relating to the broader categorisation of O&M of wind turbines. The latest Wind Industry Intelligence Skills Report produced by Renewable UK (2025) charts that there are currently a combined 10,000 wind turbine and HV electrical technicians working in the UK across both onshore and offshore projects. There is potential for this to increase to over 23,000 roles by 2030.

Looking to the future, the Everoze (2024) FLOW Taskforce report identified an opportunity to create almost 6,000 'indicative' direct and indirect jobs per year from 2030 – 2050 from O&M in floating offshore wind, specifically including activities with repair and major component replacement.

There is one example where consideration of material outflows from wind turbine decommissioning has been investigated in a study with a wider scope. Analysis conducted by Zero Waste Scotland (2023) considers the jobs impact of Scottish electric arc furnaces of various sizes with feedstocks including steel from old wind turbines and markets for outputs including high grade plate steel for new wind turbines. They found that a 300kt/yr plant could create 650 jobs; 1Mt/yr could create up to 1,000 associated jobs. There are schemes to support local employment that could be replicated elsewhere, such as offering companies involved in the Hagshaw cluster a £6k incentive for employing a local person (ZWS, 2024).

During discussions with stakeholders it became apparent that there are challenges with determining the jobs landscape directly attributable to life extension and material or component recovery. Many larger companies, such as asset owners, have relatively small, or in some cases, no teams specifically dedicated to decommissioning or life extension. Personnel are usually integrated within existing business units. Similarly, for material recovery companies, it was noted that only relatively small quantities of materials are currently being sourced from the wind industry, therefore dedicated teams may be as small as one or two personnel who draw heavily on support from the wider business. The landscape described for refurbishment companies, including some European workshops, was dominated by SME's ranging in size from micro SME's of less than five people, up to medium sized companies of 80 people.

Typical roles within refurbishment companies included sales, technicians and engineers, and research and development specialists. O&M roles were similarly defined, in addition to project managers and wind turbine technicians who are qualified to work on operational assets in the field. Interviews focused on gathering data on the jobs/roles required to carry out different activities, including MCE and decommissioning, which would directly feed into the modelling.

2.7.1 Major component exchange

Estimates provided by stakeholders for the number of staff required for onshore MCE were well aligned, with three different O&M operators stating that an MCE project would have six technicians onsite, a range of two to four crane operators, and around two additional personnel, such as site managers and drivers, with up to 10 personnel onsite in total. This high level of agreement between stakeholders increases confidence in the assumption in the required staff levels for MCE activities.

Estimates for the time required for a MCE ranged from a day for some generators, to a few days for a blade, and around 3 days for a main shaft and bearing.

“For typical major component exchange, probably looking at about six people in a week and that would cover pretty much most major component exchanges.” UK O&M company

For offshore MCE, stakeholders stated that there would typically be up to six technicians on the turbine, this is due to limited working space on the turbine itself. A jack-up vessel would also be required to provide a stable platform for a crane, with additional personnel on the Jack-up vessel. An estimate of 3 days was provided for the exchange of a gearbox as an example, excluding the upfront work required in compiling all required documentation and securing the parts. Another stakeholder provided an estimate of 30 people for the total number of personnel required for an offshore MCE.

2.7.2 Decommissioning

For onshore decommissioning projects in the range of 1-3 turbines, stakeholders described the project planning process as requiring two FTE of office staff for the securing of permits and licences. An additional FTE of sales staff was also described as being required for the 3-6 months ahead of the decommissioning for sales of the assets and components.

For the decommissioning itself, six technicians would be on site for the dismantling operations, in addition to crane operators, and site managers, for up to a week, which is similar to the process described for onshore MCE. For larger onshore windfarm projects, asset owners described having up to 20 FTE of personnel focused on the planning and execution of the decommissioning, with additional support provided by contractors for the site based work.

On discussing the resource requirements for offshore decommissioning projects, no stakeholders provided estimates for the decommissioning activities themselves. However, the decommissioning of offshore wind assets was described as being similar in scale to a construction project, with the process for offshore decommissioning having 3 phases spanning six to seven years based on the current regulatory requirements in UK. The number of project-specific staff within just an offshore operator, and not including third party contractors, was anticipated to increase from 5-10 FTE in the initial planning phase, up to a maximum of 15-20 FTE during the operational phase.

2.7.3 Future landscape

Most interviewees saw an increasing role for artificial intelligence (AI) in their future activities. Examples given included the automation of parts identification, ordering, and fault detection.

“It’ll be that there’s companies that are providing the AI software that can be tailored to your company, so if you say right, I’ve got this fault, it’ll pull up all the information about how that fault has been repaired in the past. And that will be

rolled out more and more for sure in the future. So from that respect, AI is going to have a massive impact.” UK O&M company

Some stakeholders anticipated that asset owners and operators would seek to build a greater focus on circular economy and reclaiming the value of their assets through reuse of turbines and components. This would be especially relevant as the sector gains more practical experience of decommissioning projects and turbine disassembly.

Refurbishment and O&M companies report taking on apprentices and investing in skills and training, but multiple responses discussed skills shortages for the upcoming volume of work anticipated around both life extension and decommissioning.

2.7.4 Summary of RQ employment impacts

There is limited research on the job impacts of repair and recovery activities in wind energy. Three key themes emerge: job impacts of increasing repair efforts for wind turbines, projections for the O&M sectors, and jobs linked to end-of-use material outflows. While literature is sparse, initial studies suggest potential for job creation through a circular economy, with estimates of up to 20,000 jobs in the UK by 2030. Opportunities for new jobs in offshore wind and decommissioning activities are also identified, but gaps in knowledge are substantial.

2.8 RQ 3c: GVA potential

The review found that academic literature was a poor source of information relating to GVA of material repair and recovery activities related to the wind industry. None of the academic papers reviewed made a direct attempt to calculate GVA for this type of activity, and only three academic papers made useable references to recovered material values or provided a methodology that utilised existing GVA data. Similarly, information directly discussing GVA was not gathered via the stakeholder interviews. However, some information associated with costs and revenues were provided, from which GVA assumptions can be derived. Grey literature proved to be a better source of information relating to GVA of material repair and recovery activities in wind. Four highly relevant UK focused reports specifically addressing GVA estimates relating to wind repair and recovery were reviewed.

2.8.1 Operations and maintenance

With regards to O&M, Everose (2024) calculated that UK GVA from O&M in floating offshore wind is £5770 million to 2050 with a further £9007 million from exports; this specifically includes major component repair and replacement. The GVA calculations were undertaken using five reference projects. Future O&M and decommissioning costs were discounted using a discount rate of 3.5% in the GVA calculation, aligned to UK Government good practice.

Expanding on this, stakeholders identified that MCE represents a significant cost driver within O&M activities. A large proportion of the cost for any major component exchange is the heavy lifting equipment. For onshore, this resource is typically supplied by a tower crane. The day

rate of an onshore crane for MCE can vary between £10k-100k, depending on the weight and height of the lift. For offshore, this is done with a jack up vessel, with estimated costs provided at around £100k per day of operation.

Both onshore and offshore operations require time and budget for mobilisation and demobilisation at the start and end of the activity, respectively. Both can also be significantly impacted and delayed by bad weather, which can dramatically increase the cost. For onshore assets, interview evidence suggests that the cost of the major component is comparable to the works cost of the exchange.

2.8.2 Refurbishment and reuse

Two reports explored GVA associated with wind turbine refurbishment activities. BVG Associates (2023) determined that the potential market driven by the ability to refurbish ten priority components from operational wind farms in the UK provides an estimated potential UK economic impact of £1.6 billion in GVA for the period between 2025 and 2035, and inclusion of decommissioning would likely further increase GVA potential (ZWS 2024).

In another study for Zero Waste Scotland, Jacobs (2025) estimated a GVA of £79,006 per 2MW turbine per year for refurbishment activities, with the same value (£79,006) also estimated for reuse of components. The latter figures cover only decommissioning and disposal, with the GVA calculations for end-of-life treatment options for an onshore 2 MW turbine calculated using a GVA per head ratio taken from the Scottish Annual Business Statistics 2022 (Scottish Government, 2024), with additional ratios applied using stated assumptions. GVA for life extension was not included as there are core dependencies on other processes, such as the refurbishment of components, but it was recommended this be investigated in further studies.

Resale values of smaller onshore turbines are reported to be approximately €100k/MW (£86k/MW)², around 10% of the cost of a new turbine from a European OEM. Evidence gathered in interviews highlighted that European manufacturing of new turbines is under cost competition from OEMs in Asian countries, and that turbines from China and India can be half the cost of comparable models from Europe. Stakeholders report that this cost differential has the potential to disrupt the resale market, as the saving of second-hand turbines relative to new is vastly reduced.

The reinstallation cost of a refurbished turbine is estimated to be €650k-700k (£557k-600k/MW), based on stakeholder experience of projects in the EU. Onshore turbine reuse also involves moving large items by road, invoking abnormal load requirements and dramatically increasing costs; one indication stated this can be as much as a third of the total installation cost. Stakeholders involved in this activity cited the high level of uncertainty around any project, and that value can be eroded if a buyer is not located before turbine dismantling.

² Currency conversion factor applied EUR to GBP using Bank of England average for 2025 (0.8570)

“Once the wind turbine is decommissioned then you have two options, you bring it to the new location directly, or you leave it on the ground, and you need to recycle it. Because as soon as you need to replace it, store it somewhere, double transport cost, crane cost and everything, the whole business case is gone.” EU O&M company

A common theme is that refurbishment companies will supply both new and refurbished parts. In general, revenue streams are weighted towards the sale of new parts, but stakeholders report an increasing share of income from refurbishment activities. Major components for aging turbines are commonly refurbished and these are the highest value items for companies to handle. Refurbished components are reported to be sold at lower cost than new parts. One company reports a cost saving of 60% versus a new part.

2.8.3 Recycling

With regards to material recovery, there was only one piece of grey literature that provided GVA estimates. Zero Waste Scotland (2023) considers the GVA impact of Scottish electric arc furnaces of various sizes with feedstocks including steel from old wind turbines and markets for outputs including plate steel for new wind turbines. A 300 kt/yr plant processing high value grade steel could generate a total GVA of £384M; a 1 million tonne/yr plant processing construction grade steel could generate £189M. However, GVA could vary by up to 1,500% because of likely market volatilities.

Liu et al. (2022) discuss the value retention of recycled blade materials using a crude estimation that the value of the recycled fibre is assumed to be proportional to its tensile strength (e.g. if the strength of the recycled fibre is 80% of virgin fibre, then its value is 80% of virgin fibre) with data figures only provided for the virgin material. Similarly, an approximation is also used when estimating the financial value of blade life extension, namely that when designed lifetime is 20 years and the blade life is extended by 5 years, the benefits from this life extension is 25%. In other words, a lifetime extension of 5 years saves 25% of the blade material, again the virgin fibre numbers are used for this estimation.

2.8.4 Material sourcing

While not directly addressing GVA in their work, Schreiber et al., (2025) utilise NACE Rev. 2.0 divisions and their share in Germany's GVA (€million) for scenario calculations relating to German market exposure for critical materials. The GVA figures are sourced from www-genesis.destatis.de/ for a range of metals relevant to the wind industry, including REE, Aluminium, Steel and Nickel.

When estimating material demands, Godoy et al., 2025 utilised data on import and export of manufactured products from the Eurostat database (Eurostat, 2024b), using the HS code: 850231 - Generating sets, wind-powered. This provides value in Euros and mass in 100 kg for the UK and the EU27. For the import, it was assumed their respective shares as newly installed within the EU. Conversely, for exports, their share as newly installed globally was assumed.

2.8.5 Summary of GVA potential

The GVA values quoted in grey literature suggest that repair and recovery of materials from the wind industry could be an important area for the UK economy. However, the calculation methods used for the studies and technologies assessed are variable and therefore not directly comparable, which means it is not possible to draw consensus on the provided estimates. There remains a significant knowledge gap that will need to be addressed during the phase 3 modelling.

2.9 Research review conclusions

2.9.1 Research review summary

Overall, the review results showed a great level of detail while simultaneously revealing a great number of evidence gaps. Section 2.1 (RQ 1a: Potential for repair and maintenance to support lifetime extension) assessed the potential for extending wind turbine lifetimes through repair and maintenance. Most turbines are designed for a 20-25 year lifespan, but actual lifetimes can range from under 10 years up to 50 years. Factors such as operational history, environmental conditions, and market regulations influence decisions around lifetime extension. Countries like Germany and Denmark have regulations for safety and structural assessments, while the UK lacks clear guidelines, an issue reinforced by interview findings, where the absence of life extension standards was identified as a potential constraint on both project execution and supply chain participation.

The UK onshore wind fleet is already undergoing life extension, with site specific decisions primarily determined by access to spare parts and the continued costs of ongoing operations. There was a strong consensus that assets are typically run to 30-35 years, which narrows the data range identified in phase 1; however, a significant data gap remains on the maximum technical life that can be achieved. Limiting factors may also be applied by consenting, land ownership issues, and network capacity for repowering projects. The offshore wind fleet, by contrast, has not yet reached sufficient maturity to consider life extension on the same scale, but there is a general view that the same approach will be applied and that offshore life extension offers an opportunity to contribute to UK energy security efforts.

Failure, repair and replacement rates for wind turbines are critical factors for lifetime extension, but empirical information is patchy and varies substantially. Interviews confirmed that component failure rates are largely uncaptured and unquantifiable, meaning this key knowledge gap persists. Blades and bearings most commonly experience issues. While technological advancements such as direct-drive systems and improved diagnostics can reduce failure rates and intelligent maintenance systems, like IoT-based solutions, offer potential for cost savings, they may also lead to increased costs and data security challenges. Across both onshore and offshore sectors, asset owners are increasingly adopting a more data-driven, proactive O&M approach with condition monitoring playing a key role.

Nevertheless, many onshore assets are still run to failure and industry-wide barriers to O&M data sharing remain significant.

Section 2.2 (RQ 1b: Net-impact on material demand) shows that extending turbine lifetimes may reduce material demand in the short to medium term, as extending the use of existing turbines delays the need for full replacements. Global studies suggest that lifetime extensions can reduce material demand by 5-15%, with more significant reductions in the long term. The results suggests that domestic recycling and manufacturing will have a greater long-term impact on reducing material demand compared to lifetime extension alone.

Section 2.3 (RQ 1c: Net-impact on emissions) shows that extending turbine lifetimes can reduce GHG emissions up to 35%, with postponed decommissioning (possibly supported by reused and refurbished parts) and material reuse contributing to these savings.

Section 2.4 (RQ 2a: Potential for component reuse and material recovery) shows a decrease in material intensity over time and identifies substantial potential for reuse of turbines and components.. When turbines reach EoL, a clear hierarchy is observed: whole turbine reuse, followed by component reuse, and finally material recovery. These activities are already occurring in the UK to some extent, although no robust data exists on the distribution between these pathways, representing an ongoing evidence gap. Reuse and recovery from first-generation turbines could significantly reduce waste. Steel and copper dominate turbine waste streams, while recycling of REEs remains limited due to high processing costs. Offshore turbines, which are larger and more material-intensive, are expected to drive significant increases in material demand by 2040. Blade waste, projected to rise globally, presents an early and pressing challenge in Europe. The UK currently has a small but growing component refurbishment industry, creating emerging secondary markets and new revenue streams. However, interviewees raised concerns that a lack of pipeline certainty is limiting investment, leading to missed economic opportunities and continued export of components to the EU. There are also concerns about insufficient domestic capacity to manage increasing material volumes from future decommissioning projects.

Section 2.5 (RQ 2b: Quantitative economic, technical, social and environmental values) suggests that recycling metals like steel offers economic potential, but recycling turbine blades and REEs presents greater challenges due to low recovery value and high treatment costs. Environmental impacts mostly focus on blades and the review underlines landfilling as the least favourable option, suggesting pragmatism with mechanical recycling first while growing blade waste enables more energy-intensive methods such as pyrolysis and solvolysis for higher recycling performance.

Section 2.6 (RQ 3a: Economic impacts of repair and recycling) reveals high variation in the findings and thereby negates consensus. Onshore and offshore wind may have fundamentally different business cases for lifetime extension, due to the 2-3 times higher O&M costs in the marine environment. Preventative maintenance has high potential to reduce costs, with early repairs reported to save 2-12.5% of costs and condition-based maintenance a further 8% saving in O&M costs. Repairing or partially repowering wind turbines is generally cheaper than

full replacement. A secondary market for refurbished parts has started to create new revenue streams. Blade recycling is constrained by high costs while REE recycling face volatile prices and technical challenges.

Section 2.7 (RQ 3b: Employment impacts) shows high potential but uncertainty about job creation, with limited evidence sources to draw upon. Repair, recovery and recycling could create substantial job opportunities, with estimates of up to 20,000 jobs in the UK by 2030. Interviews also provided new estimates for labour requirements and costs associated with MCE operations, and decommissioning, which will inform phase 3 modelling. Policy incentives are critical for enabling blades and magnets solutions with a difficult economic case.

Section 2.8 (RQ 3c: GVA potential) suggests high potential for the UK economy, but the evidence base is too unreliable for a consensus result.

3 Phase 3: Quantitative modelling

3.1 Methodology

3.1.1 Purpose and scope of quantitative modelling

3.1.1.1 Purpose of quantitative modelling

The purpose of the quantitative modelling is to provide scenarios on material stock and flows from the UK's installed onshore and offshore wind turbine fleet (including foundations) to quantify the impacts on material demand, emission reductions, job creation, and GVA to the UK economy until 2050. Accordingly, scenarios were constructed to allow for assessing the fleet's potential for lifetime extension, second lifecycle practices, and material recovery of selected components and materials. To capture the full decommissioning and material handling lifecycle phases for each life extension scenario, a timeline until 2070 was used.

For a better understanding, Table 8 outlines the contribution of the quantitative modelling to the overall RQ of the project. Material stock and flow modelling, economic impact modelling, and emissions impact modelling provide outputs to almost all research questions. The one exception being RQ 1a, which is purely answered by the outputs of the research review phase, and functions as input to the material flow modelling, and as such lays the foundation to answer RQ 1b and RQ 1c.

Table 8: Quantitative modelling contribution to the research objectives and questions.

Research objectives	Research questions	Contribution to modelling
1. Identify to what extent repair and maintenance can help extend the lifetime of existing onshore and offshore wind energy technologies.	a. To what extent can repair and maintenance help extend the lifetime of existing wind turbines?	Input to material flow model
	b. What is the net impact on material demand associated with extending the lifetime of wind assets?	Output of material flow model
	c. What is the net impact on emissions associated with extending the lifetime of existing onshore and offshore wind assets?	Output of emissions impact model
2. Quantify how much material and reusable components can be	a. How much material and reusable components can be recovered from existing onshore and offshore wind assets?	Output of material flow model

Research objectives	Research questions	Contribution to modelling
recovered from existing onshore and offshore wind assets.	b. What is the best (i.e. highest value) use of recovered materials and components?	Comparison of overall scenarios and sensitivity analyses, based on all models
3. Identify economic impacts of examine repair & recovery activities for wind assets.	a. What are the potential economic impacts of the repair and recovery activities identified by the research?	Output of economic impact model
	b. What are the respective potential job impacts for repairing and recovering material from existing wind assets?	Output of economic impact model
	c. What is the potential GVA to the economy by repairing and recovering material from existing wind assets?	Output of economic impact model

3.1.1.2 Scope of quantitative modelling

The answers to the RQs are given by considering the modelling scope outlined in Table 9.

Table 9: Scope of quantitative modelling.

Topic	Scope of quantitative modelling
Fleet	<ul style="list-style-type: none"> UK's onshore and offshore wind turbine fleet of installed wind turbines and wind parks under construction. Hence, future installations are out of scope
Wind technology	<ul style="list-style-type: none"> Onshore and offshore wind turbines and foundations. Other infrastructure such as external cables, substations or scour protection are out of scope Common turbine type of horizontal axis turbine with three blades, and for onshore also some wind turbines with two blades Turbines with a minimum installed capacity of 50 kW. Thus, household wind turbines are out of scope

Topic	Scope of quantitative modelling
Selected materials	<ul style="list-style-type: none"> • Steel of wind turbine and foundation/substructure • Concrete of foundation/substructure • Composites from blades
Lifecycle stages	<ul style="list-style-type: none"> • Operation (incl. major component replacements), decommissioning and handling of decommissioned wind turbines and foundations/substructures

The scope includes the UK's existing onshore and offshore wind turbine fleet, considering the common technology of horizontal-axis wind turbines with three blades. For onshore, two bladed turbines installed in the UK are also considered. Small household wind turbines are excluded, as these are different technologies with different market mechanisms, and only play a minor role in overall material quantities. In addition, wind parks that are installed or are under construction until 2027 are considered in the modelling, while future wind installations are out of scope.

Following the findings of the literature review, steel, concrete, and composites are selected for the quantitative modelling, as these materials make up most of the mass of a wind turbine and its foundation (Tota-Maharaj et al., 2021). Steel and concrete account for by far the largest share of mass; in onshore mostly concrete, while in offshore predominantly steel, which is due to the different types of foundations/substructures. Various components of a wind turbine contain steel, most of which comes from the tower and, in the case of offshore turbines, also from the substructure. Concrete is found in the foundation/substructure of onshore turbines, gravity base offshore turbines, and some floating offshore turbines.

Furthermore, composites are in scope, as recycling infrastructure still needs to be scaled up in the UK and generally in Europe (see section 2.4.2.1 and 2.4.1.2). It is therefore vital to understand whether the expected material flows from UK's existing wind farm fleet are sufficient to reach the economic viability threshold of roughly 5,000 to 15,000 tonnes per year for a new composite recycling facility (Kramer et al., 2024). The study considers composites from the blades, which account for the majority of the composite materials used. Furthermore, as discussed in section 2.4.1.2, other industries (including construction, marine) have a larger expected mass of composites than wind turbines, and this assessment would therefore benefit from a cross-industry analysis. Research into possible recycling technologies and impact assessments of various recycling solutions are currently still ongoing, meaning that the question of whether a closed or open recycling infrastructure (i.e. blade-to-blade or blade-to-X) should be pursued remains to be clarified.

In addition to steel, concrete, and composite materials, a wind turbine contains other materials such as copper, REE, and aluminium. These materials account for only a small fraction of the

total weight of the turbine and are not in the scope of this study. However, when the expected decommissioning and waste volumes of the entire wind turbine fleet are added together, they can still be relevant for resource and waste management in the UK. The results of the literature review highlight in particular the importance of quantifying material flows of critical raw materials for existing and future industries (section 2.4.1). It is therefore recommended that further materials be integrated into material flow modelling in future work. The methodology can be easily transferred to other materials and could therefore be expanded accordingly in future studies.

Table 9 outlines that the operation (including major component replacements), decommissioning and handling of decommissioned wind turbines, their components and materials as well as of foundations/substructures are in scope.

In summary, Figure 1 provides a high-level overview of the modelling framework.

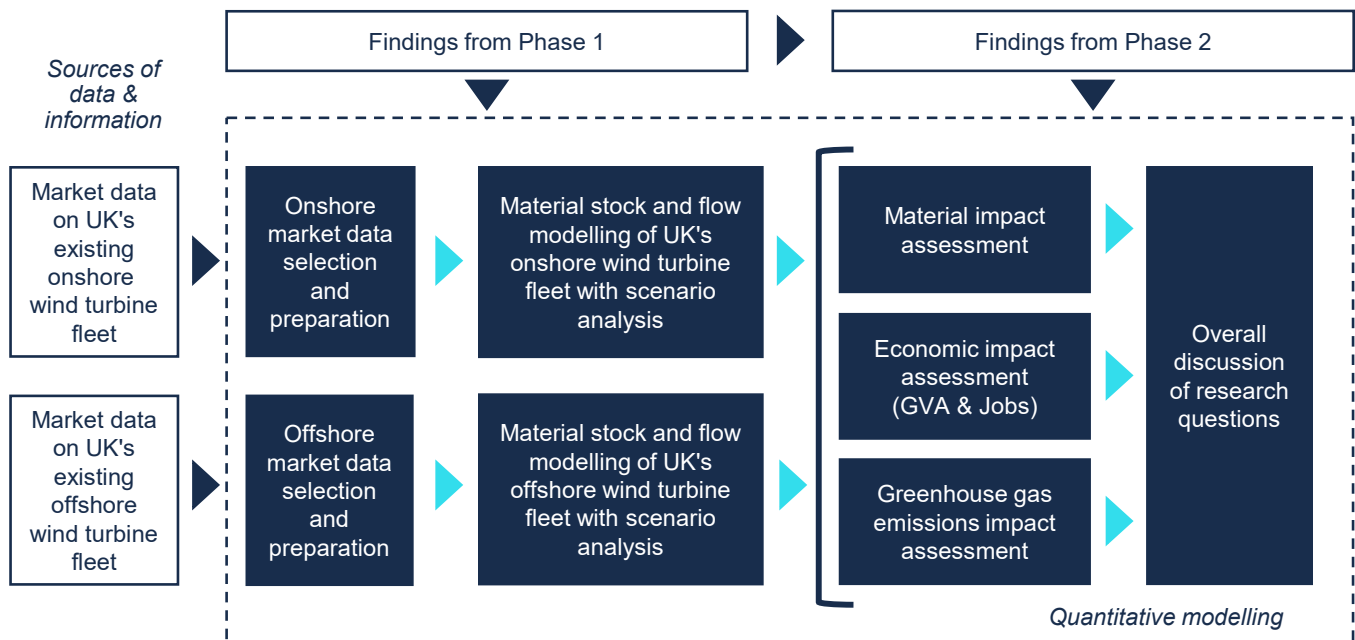


Figure 1: Overall modelling framework for Phase 3, outlining the modelling of material stocks and flows, as well as the assessments of material use, GVA, jobs and emissions.

Consequently, the methodological approach applied to the existing UK wind turbine fleet comprises of three main areas, which are further detailed in the following sub-sections:

- Material flow modelling (section 3.1.2)
- Economic impact assessment (section 3.1.3)
- Emissions impact assessment (section 3.1.4)

Note that while onshore and offshore wind markets are generally treated as distinct markets with their own supply chains, involving different players and policy frameworks, there are also areas of overlap between them. This report therefore distinguishes between these technologies while acknowledging such intersections. The material flow models of each

technology are aggregated at the end to also show the total material flows of the UK wind turbine fleet.

3.1.2 Material flow modelling

The material flow modelling focuses on RQ1b and RQ2a, as outlined in Figure 2. The objective is to model the material flows across the value chain stages: i. installation, ii. operation and maintenance, iii. decommissioning, and iv. the handling of the decommissioned wind turbines (including foundation).

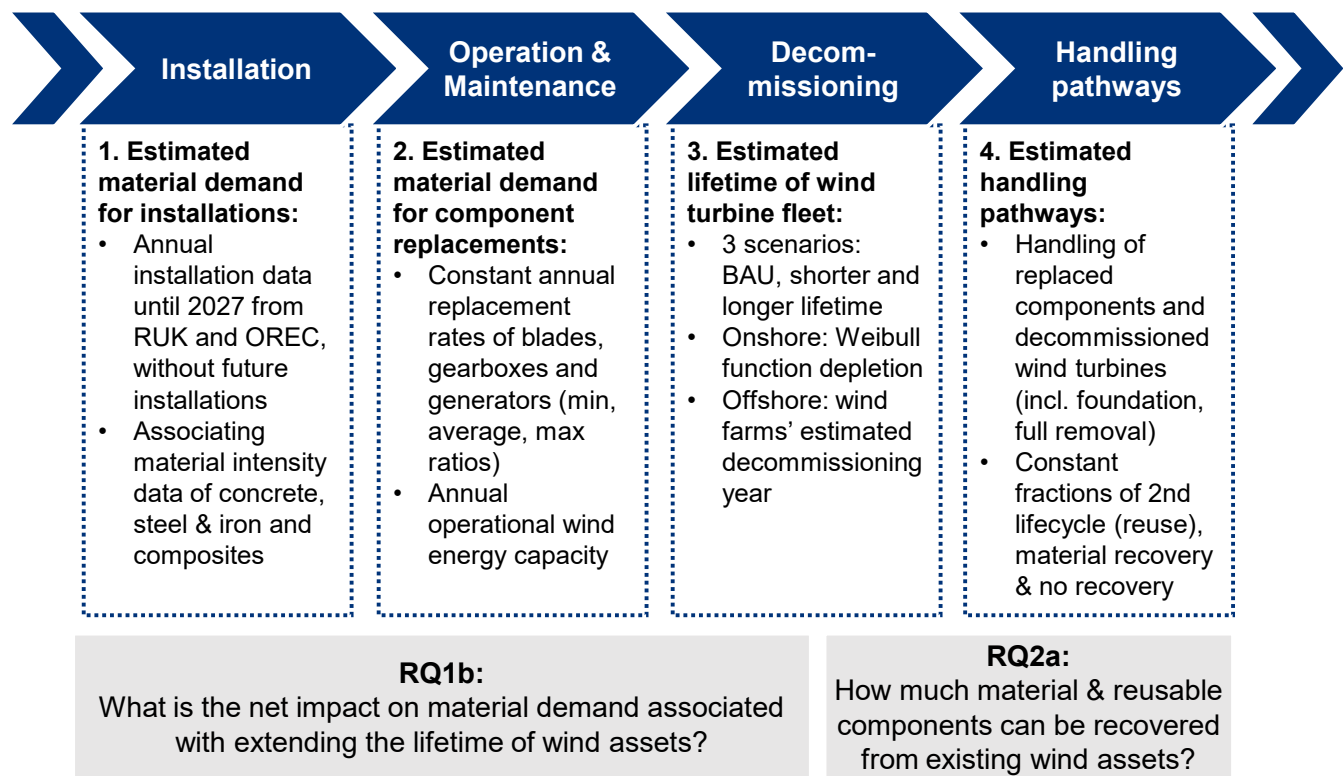


Figure 2. Overview of material flow modelling methodology.

The following describes the fleet market data (chapter 3.1.2.1), followed by the material flow modelling and scenario development (chapter 3.1.2.2).

3.1.2.1 Data on UK's onshore and offshore wind turbine fleet

3.1.2.1.1 Selection of fleet market data

The objective is to select a dataset that comprehensively represents the history of installations and decommissioning of onshore and offshore wind turbines in the UK.

To ease replicability of the methodology, publicly and freely available data are preferred. The UK Government publishes the Renewable Energy Planning Database (REPD) on a quarterly basis with the latest version being Q3 2025 at the time of writing this report. However, significant data gaps exist in the REPD (e.g. decommissioning date, turbine model, rotor diameter, incomplete hub height data) and therefore this dataset is not used. Besides UK government, WindEurope and the Global Wind Energy Council (GWEC) provide annual

statistics on UK's onshore and offshore installations, however, only annual values (in MW) on aggregated national level are provided which does not allow for modelling flows on wind farm and turbine level.

To allow for detailed analyses and more detailed and robust modelling of the material stocks and flows, the following proprietary datasets were selected for this study:

- Onshore wind turbine fleet data by RenewableUK (RUK). The dataset was provided on 22/01/2026 in Excel format with data as of 31/12/2025. Material intensity data was associated according to methods from scientific literature.
- Offshore wind turbine fleet data by Offshore Renewable Energy Catapult (ORE Catapult) as their database on UK offshore wind farms also include material intensity data, which the others do not. The fleet data is based on 4C Offshore data. The dataset was provided on 12/12/2025.

A detailed overview of the fleet market data quality assessment and data preparation is shown in Appendix Data on major repairs that are defined as repairs that require a jack up vessel, but it's not broken down further than that for repair/replace, nor is it broken down per component. Only the number of forced outages is presented per component.

B.1.2 Fleet data quality assessment.

3.1.2.2 Material flow modelling and scenario development

The objective is to develop scenarios for material stock and flows associated with the UK's installed onshore and offshore wind turbine fleet, including foundations, up to 2050.

The developed model enables the quantification of net material demands for life extension of existing wind turbines (RQ 1b), as well as estimating the recoverable materials and reusable components from existing wind assets (RQ 2a).

The methodology is based on Kramer (2025) and has been adapted to the UK context and defined scope of this study, incorporating literature and stakeholder insights gathered in the research review. A comprehensive overview of the assumptions taken in the material flow models is provided in Appendix B.2 [Material flow assumptions](#). Key assumptions are summarised in the following sub-sections.

[3.1.2.2.1 Expected lifetime of wind turbine fleet](#)

To address the first research objective, the core assumptions for estimating fleet lifetimes and component replacement rates during operation are defined. This results in scenarios on expected lifetime distributions of the fleet and material demand for major component replacements.

[3.1.2.2.1.1 Scenarios on onshore and offshore fleet's operation and time of decommissioning](#)

Three scenarios are defined: a business-as-usual (BAU) scenario, a shorter lifetime scenario, and a longer lifetime scenario. Table 10 provides an overview of the defined scenarios, which are described in detail below.

Table 10: Overview of parameters to model the fleet’s lifetime distribution according to a business-as-usual scenario, shorter lifetime scenario and longer lifetime scenario.

	Business-as-usual (BAU) scenario	Shorter lifetime scenario	Longer lifetime scenario
Onshore	Weibull $\lambda = 33, k = 12$	Weibull $\lambda = 26, k = 12$	Weibull $\lambda = 35, k = 12$
Offshore	30 years	25 years	35 years

Onshore wind – BAU, shorter lifetime and longer lifetime scenario

The method is based on Abrahamsen et al. (2023), Kramer et al. (2024), Kramer (2025) and Mc Govern et al. (2025). The resulting depletion function of each scenario for the onshore wind fleet is shown in Figure 3. These are compared to a 20-year design life (orange line, based on Section 2.1.3), and the ratio of annual decommissioned to installed capacity (dark blue).

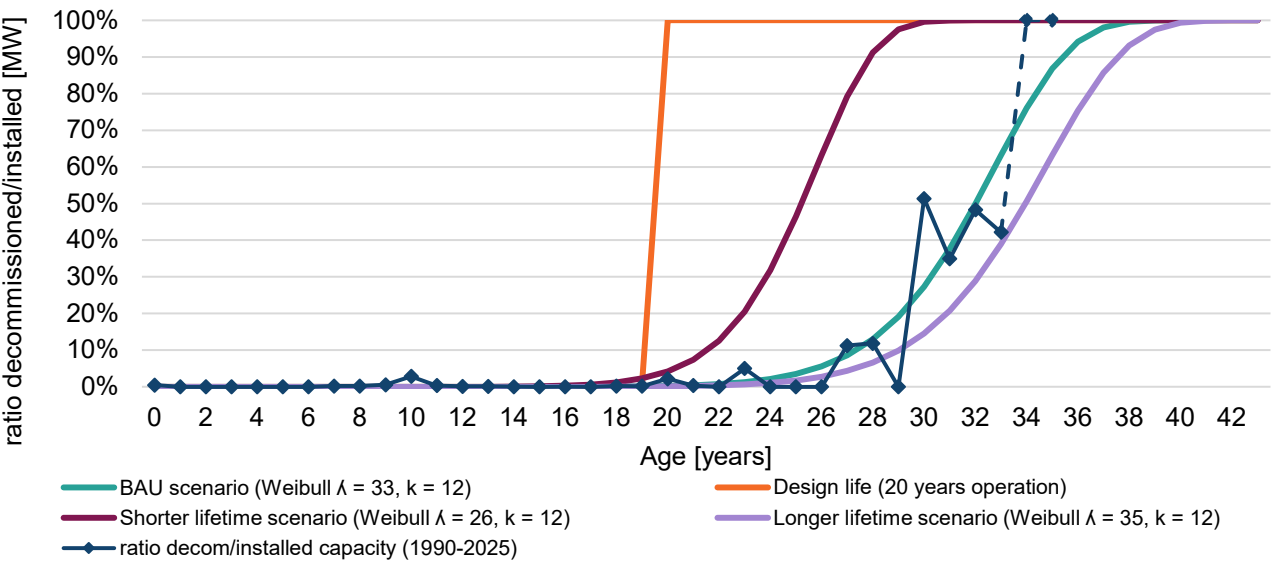


Figure 3: Overview of scenarios for estimating the time of decommissioning of UK's onshore fleet, using different Weibull functions. Calculations of the ratio decom/install is based on data by RUK (RenewableUK, 2025).

Offshore wind – BAU, shorter lifetime and longer lifetime scenario

The first commercial offshore wind farm in the UK was fully commissioned in 2004. Only two offshore wind demonstrators have been decommissioned in the UK: the original two Blyth turbines were decommissioned in 2019 (not part of the database), and the 2 MW demonstrator of Kincardine Phase 1 was decommissioned in 2020 with the replacement of the full-scale wind farm (Kincardine - phase 2 with 5 turbines). Overall, only two offshore wind farms have operated for more than 20 years, and none have exceeded 25 years of operation to date.

The lifetime assumption for each offshore wind scenario is shown in Figure 4, which is based on the parameters outlined in Table 10.

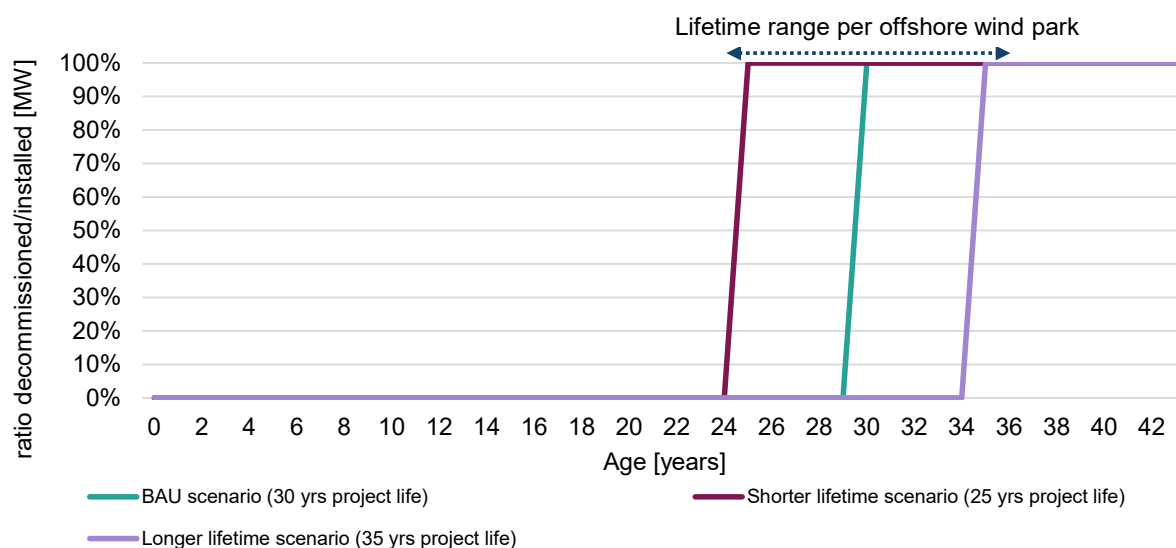


Figure 4: Overview of scenarios for estimating the time of decommissioning of UK's offshore fleet.

The assumed decommissioning timing has a strong influence on projected material flows of steel, iron, and composite materials. This is particularly relevant for the 53 offshore wind farms included in this study, which are either already installed or expected to be fully operational by 2027. As a result, project-level decision-making has a substantial impact on aggregate material flows in the offshore sector, more so than in the onshore sector. Given this sensitivity, future work should consider a project-level assessment incorporating factors such as permitting and lease conditions, CfDs, Power Purchase Agreements, turbine type, developer strategy, and grid connection.

Based on these considerations, this study applies a simplified approach using constant lifetime assumptions per wind farm and scenario, rather than a full depletion function for offshore decommissioning. The scenarios are therefore interpreted as lifetime ranges: 25 years (short), 30 years (BAU), and 35 years (long). Earlier projects are more likely to align with the shorter lifetime assumption, while newer installations are more consistent with longer lifetimes. The results should therefore be interpreted as scenario ranges for material flows rather than precise annual trajectories. Finally, it is recommended that offshore and onshore results are analysed separately, and that interpretation focuses on 5-year intervals rather than annual fluctuations.

Further details on the lifetime estimation process of wind turbine fleet is outlined in Appendix B.1.3 Expected lifetime of wind turbine fleet.

3.1.2.2.1.2 Component replacement rates for operating onshore and offshore wind turbines

Different approaches exist in literature to model failure rates resulting in minor and major repairs or component replacements. The research review identified studies that consider replacement rates in material flow forecasting or explored failure rates of operational onshore

or offshore wind turbines. For example, Schreiber et al. (2019), Peng et al. (2023), Shammugam et al. (2019), Tota-Maharaj et al. (2021) and Godoy León et al. (2025) outline replacement rates for components of onshore and offshore wind turbines (see section 2.1.2.1 for further details). Theoretically, the failure rates of a wind turbine are expected to follow a 'bathtub curve' depending on its age, where more failures occur during early operation, stabilise during the mid-life phase, and increase again towards the end of lifetime (Walgern et al. 2026). According to Walgern et al. (2026), this pattern is also observable for certain sub-systems, such as the drivetrain, whereas other components, such as central hydraulic systems, may exhibit a more continuously increasing failure trend.

Despite this, many material flow studies do not explicitly model the material mass generated from replacements during O&M, instead focusing solely on end-of-life decommissioning flows. Furthermore, the literature review shows that publications with **empirical data on failure rates, especially for ageing turbines, remains limited**. For instance, the SPARTA report (2022) provides valuable insights into repair and replacement data for offshore wind turbines in the UK but only outlines results for the turbine age of 0-10 years. The study finds that a peak in repairs occurs shortly before the OEM warranty ends, and then slowly increases from 8-9 years onwards. However, the analysed fleet covers turbines aged only up to 17 years, meaning that lifetime extension effects are not captured. Similarly, example, Carrol et al. (2015) provide comprehensive empirical data, but based on European offshore wind farms with an age between 3-10 years.

Supporting this, the findings from the stakeholder interviews indicate that the extent to which repairs and component replacements can extend wind turbine lifetime remains largely uncertain. This is due to the influence of multiple factors, including turbine design, site-specific wind conditions, and operational strategy, as well as limited empirical experience, particularly for offshore wind.

It is therefore recommended that further research be conducted to collect additional empirical data from both onshore and offshore wind fleets in order to better understand how replacement rates evolve with turbine age across different turbine designs, as well as how predictive maintenance strategies may contribute to reducing failure rates. In addition, future work should more explicitly link replacement-rate modelling with the estimation of remaining technical lifetime at both turbine and component level. This would support the development of more effective operation, maintenance, and repair strategies, and improve the robustness of material flow modelling.

Given the scarcity of consistent empirical data and the resulting uncertainty in parameter selection, a sensitivity analysis is conducted using minimum, maximum, and average values from Table 11. For offshore blades, a base value of 3% is applied and varied by $\pm 1\%$. As more empirical data becomes available, it is recommended that future work develops differentiated failure rates that explicitly account for turbine design, O&M strategy, and component ageing over time. In addition, future analyses should consider component replacements that contribute to lifetime extension, such as converter upgrades and other retrofit measures (Anderson, 2024).

Table 11: Summary of model assumptions for annual replacements of selected major components.

Replacement rate per wind turbine p.a.	Model assumption onshore (average of studies)	Range from onshore wind studies	Model assumption offshore (average of studies)	Range from offshore studies
Blades (p_{blade})	2.2%	2.0%-2.3%	3.0%	0.1%, 3%
Generator ($p_{generator}$)	2.6%	0.7%-10.9%	3.3%	0.3%-10.9%
Gearbox ($p_{gearbox}$)	4.6%	3.1%-5.9%	5.6%	0.9%-15.4%

The next step is to link component replacement rates to the corresponding material masses of wind turbine components. Composite blade waste in year n is calculated by multiplying the operational composite blade stock in year n by the average annual blade replacement rate p_{blade} (see Table 11).

For steel and iron flows from generator and gearbox replacements in year n , the number of operational turbines is first multiplied by the average annual generator replacement rate $p_{generator}$ and gearbox replacement rate $p_{gearbox}$ (see Table 11). The resulting number of gearbox replacements is then adjusted to account for drivetrain configuration, as not all turbines are equipped with a gearbox. Since the datasets do not fully capture drivetrain type, additional data were collected for 65% of the onshore fleet and 100% of the offshore fleet. Based on this, approximately 85% of onshore turbines use a geared drivetrain, while 15% are direct-drive systems. For offshore wind, 26.5% of turbines are geared and 73.5% are direct-drive systems. In the final step, the number of replacements is multiplied by the average generator mass and average gearbox mass of the installed fleet (see Table 12). For onshore, an average mass for 2-4 MW turbines was used, given that the average turbine size weighted by total installed capacity equals 2.8 MW. For offshore, more detailed data was available and therefore the average of the UK offshore fleet calculated and used.

Table 12: Steel & iron mass of generator and gearbox of onshore and offshore wind turbines. Based on ORE Catapult calculations.

Steel & iron mass [t]	Onshore (average 2-4 MW turbines)	Offshore (average of UK fleet)
Generator (geared)	9.4 t	18.1 t
Gearbox	39.2 t	80.2 t

Steel & iron mass [t]	Onshore (average 2-4 MW turbines)	Offshore (average of UK fleet)
Generator (direct drive)	50.9 t	159.0 t

As a result, the model produces the following annual outputs, which serve as inputs to the economic and emissions impact assessments:

- Annual number of blade replacements and associated composite mass in tonnes
- Annual number of generator and gearbox replacements with associated steel & iron mass in tonnes

The process used to determine the component replacement rates is detailed in Appendix B.1.4 Component replacement rates.

3.1.2.2.2 Decommissioning and handling of decommissioned wind turbines, foundations and major component replacements

To address the second research objective, the circular economy pathways the wind turbine fleet, its components and materials will take after decommissioning or component replacement are set out. This results in scenarios estimating the potential quantities of reusable turbines and components, as well as materials available for domestic recycling.

As a reference framework for the definition of handling pathways, the industry neutral 9R-ladder by Potting et al. (2017) is applied, which eases transferability to other industries. The relevant R-principles considered after decommissioning, ranked from higher to lower sustainability value, are: reuse (R3), repair (R4), refurbishment (R5), remanufacturing (R6), repurposing (R7), material recycling (R8) and energy recovery (R9) (Velenturf, 2021; Kramer et al., 2024).

For the purposes of material flow modelling, these pathways are aggregated into three categories: (i) second-life applications of turbines or components (R3–R6), (ii) material recovery pathways (R7–R8), and (iii) pathways without material recovery (R9 and landfilling). This aggregated approach makes it possible to compensate for the currently limited availability of empirical data for the UK, (see section 2.5.1), while taking account of the structure of RQ 2b. regarding a cascading flow of materials and components.

Constant shares are assigned to each pathway across the defined scenarios, complemented by a sensitivity analysis exploring alternative distributions. As more empirical data becomes available, future work should refine this approach by introducing time-dependent pathway shares that reflect industry developments, as well as potential regional variations across the UK.

The scope of the material flow model covers post-replacement and end-of-life handling processes but does not include a second use phase of turbines or components, nor the incorporation of recycled materials into new products.

The following sections first outlines the expected share of removal from the project sites (Section 3.1.2.2.2.1), followed by outlining the scenarios for reuse (Section 3.1.2.2.2.2), material recovery and no recovery (Section 3.1.2.2.2.3).

3.1.2.2.2.1 Removal from project site

For onshore wind turbines, it is assumed across all lifetime scenarios that 100% of turbines and their foundations are removed from the project site, i.e. no on-site burial or partial decommissioning is considered. However, insights indicate that partial foundation removal is currently common practice in the UK (see section 2.4.2.2.2). The RUK dataset does not provide information on foundation types or installation depths, such as the distribution between shallow and deep foundations, limiting the ability to reflect different decommissioning practices.

As a result, reported quantities of concrete, and a fraction of steel and iron associated with foundations, should be interpreted as upper-bound estimates for material handling.

For offshore wind turbines, the same assumption of 100% removal of turbines and foundations is applied across all scenarios. At present, there is no internationally standardised approach to offshore decommissioning, reflecting the limited operational experience worldwide. However, ongoing research and consultation efforts aim to develop more robust guidance on decommissioning practices, including the extent of foundation or substructure removal and associated environmental impacts (e.g. material use and biodiversity).

This uncertainty is particularly relevant for steel and iron flows, and for floating foundations also for concrete. Accordingly, the model assumes full removal in all cases, although actual practice may vary depending on site-specific conditions. Therefore, all reported quantities should be interpreted as maximum material flows requiring processing.

3.1.2.2.2.2 Scenarios on reuse of decommissioned wind turbines and component replacements

According to findings of the literature review (Struthers and Pitts, 2025) and the stakeholder interviews (see section 2.5.1), the UK is an active participant in the second-hand market, both as a buyer and seller of onshore wind turbines, components, and parts, while experience from offshore decommissioning is still limited, but expected to be lower in comparison to onshore.

The scenarios on setting reuse fractions for the expected decommissioned wind turbines and component replacements, are based on the following rationale:

- For decommissioned wind turbines: to account for differences in remaining useful life across the scenarios, it is assumed that the earlier lifetime scenario has the highest reuse potential, followed by the BAU scenario and then the longer lifetime scenario.
- For components handled from O&M replacements: the reuse potential in the longer lifetime scenario is expected to be the largest, followed by the BAU scenario and then

the shorter lifetime scenario. This reflects the increased demand for second-lifecycle components as turbines age, due to the reduced availability of new components.

Table 13 summarises the findings on the reusability of key components, distinguishing between reuse as part of a complete turbine and reuse as individual spare parts. Strengthening this distinction in future research will be important, as these represent separate demand markets and require different strategies for managing material flows.

Table 13: Overview of reuse potential of key components. Inspired by Kramer (2025), Struthers and Pitts (2025) and phase 2 findings.

Onshore		Offshore	
Tower	If not reused as part of whole turbine sale, second lifecycle to be expected negligible.	Second lifecycle as part of reinstalling whole turbine or as spare parts. For generator, gearbox and yaw system higher reuse rates are expected than for blades.	
Nacelle cover			
Hub			
Generator			
Gearbox			
Yaw system			
Rotor blades			

Vestas reported an overall refurbishment ratio for their global service business of 32% in 2025, while targeting 55% by 2030 and 75% by 2040 (Vestas, 2021; Vestas, 2025). These figures are not region-specific, but they indicate a substantial and increasing role of refurbishment, particularly for major components. Given that Vestas accounts for approximately 24% of installed onshore capacity and 22% of offshore capacity in the UK, this provides a useful indication of the potential for component reuse during operation, even though not all turbines are necessarily under Vestas service contracts. In contrast, one of the interviewed stakeholders suggested that for less in-demand turbine models, component resale rates can be as low as 5% by mass. In addition, while the resale of minor parts (e.g. individual drivetrain components such as brake callipers) is described as common practice, no comprehensive data is currently available. It is therefore recommended that future studies collect more detailed data on these material flows.

The reuse potential also depends on how quickly the fleet is depleted (k parameter of the Weibull function), on the characteristics of the UK and other wind markets, and consequently on the potential demand for spare parts to maintain operations. Furthermore, as highlighted throughout the report, there is a general lack of data and practical experience regarding the technical life of turbine models and thus their remaining useful life. This limitation also affects the assessment of the potential of the second-hand market, meaning that the assumptions

presented should be regarded as informed estimates. Moreover, while turbine age provides a useful proxy, it is not a definitive indicator of condition, as performance and degradation are influenced by multiple factors, including turbine design, maintenance strategies, and site-specific conditions. It is therefore recommended that future work further investigates reuse potential and refines the underlying model assumptions.

A comprehensive summary of the estimation method used for material reuse is outlined in Appendix B.1.5 Turbine and component reuse, and the assumptions are summarised in Table 14 in Section 3.1.2.3.

3.1.2.2.2.3 Scenarios on material recovery or no recovery

Material quantities not channelled into the second-hand market are to be processed as waste. The material flow model distinguishes between material recovery (e.g. repurposing, mechanical recycling, pyrolysis, solvolysis) and no material recovery (e.g. landfilling, incineration with energy recovery). Future work could refine this classification by distinguishing between high, mid, and low-value recycling as well as between open (e.g. blade-to-x) or closed-loop recycling (e.g. monopile-to-monopile or blade-to-blade).

Uniform recovery fractions are used across all lifetime scenarios and for both onshore and offshore, as unlike the reuse potential, these are not impacted by turbine age. However, for future analysis aimed at informing industry policies, it may be valuable to integrate scenario-specific variations to account for the different timings of the material flows. For instance, if material recycling infrastructure (e.g. for composite) still needs to be scaled in the UK – the BAU scenario and longer lifetime scenario provide more time for the establishment of the infrastructure.

Further details on material recovery rates for steel and iron, concrete and composites are outlined in Appendix B.1.6 Material recovery, and summarised in Table 14 in Section 3.1.2.3.

3.1.2.3 Scenario definition overview

Table 14 outlines the main parameters for each scenario definition, including the baseline and sensitivity analysis values.

Table 14: Overview of scenario definitions and sensitivity analysis parameters.

Parameter	BAU	Shorter Lifetime	Longer Lifetime
Lifetime	Onshore: - Weibull $\lambda = 33$, $k = 12$ Offshore: - 30 years	Onshore: - Weibull $\lambda = 26$, $k = 12$ Offshore: - 25 years	Onshore: - Weibull $\lambda = 35$, $k = 12$ Offshore: - 35 years

Parameter	BAU	Shorter Lifetime	Longer Lifetime
Replacement rates per wind turbine	Onshore: <ul style="list-style-type: none"> - Baseline: 2.2% (blades), 2.6% (generator), 4.6% (gearbox) - Min: 2% (blades), 0.7% (generator), 3.1% (gearbox) - Max: 2.3% (blades), 10.9% (generator), 5.9% (gearbox) Offshore: <ul style="list-style-type: none"> - Baseline: 3% (blades), 3.3% (generator), 5.9% (gearbox) - Min: 0.1% (blades), 0.3% (generator), 0.9% (gearbox) - Max: 3% (blades), 10.9% (generator), 15.4% (gearbox) 		
Material reuse	Onshore foundation (baseline): <ul style="list-style-type: none"> - 0% for foundation, therefore 0% for concrete. Offshore foundation (baseline): <ul style="list-style-type: none"> - 0% for foundation, thus 0% for concrete and 0% for steel and iron mass of foundation. 		
	Onshore (baseline): <ul style="list-style-type: none"> - 21% of steel, iron and composite mass Offshore (baseline): <ul style="list-style-type: none"> - 12% of steel, iron and composite mass 	Onshore (baseline): <ul style="list-style-type: none"> - 26% of steel, iron and composite mass Offshore (baseline): <ul style="list-style-type: none"> - 19% of steel, iron and composite mass 	Onshore (baseline): <ul style="list-style-type: none"> - 13% of steel, iron and composite mass Offshore (baseline): <ul style="list-style-type: none"> - 10% of steel, iron and composite mass
	Material reuse sensitivities <ul style="list-style-type: none"> - -10% of second lifecycle fraction - +10% of second lifecycle fraction - +20% of second lifecycle fraction <p>For the foundations the assumption to directly enter waste handling is not changed.</p>		

Parameter	BAU	Shorter Lifetime	Longer Lifetime
Material recovery ³	<p>Onshore and Offshore (baseline):</p> <ul style="list-style-type: none"> - 50% material recovered of concrete - 95% material recovered of steel and iron - 50% material recovered of composite <p>Material recovery sensitivities (%):</p> <ul style="list-style-type: none"> - 0%, 25%, 75%, 100% material recovered of concrete - 5%, 25%, 50%, 75% material recovered of steel and iron - 0%, 25%, 75%, 100% material recovered of composite 		

The application of the methodology yields annual estimates of turbines remaining in operation (including lifetime extension), turbines to be decommissioned, and the corresponding quantities allocated to second-life use, material recovery, and non-recovery pathways for selected material flows.

The results of each scenario are presented in Section 3.2 and the conducted sensitivity analyses provide further insight to guide the discussions and the impact assessments.

3.1.3 Economic impact modelling

This section outlines the methodology used to estimate the GVA to the economy and the net job impact of repair and recovery activities. The model relies on two inputs:

1. The output from the material flow models.
2. Conversion ratios to transform material flow data into GVA or job impact data.

These ratios have been determined using either data from the ONS or through literature reviews and interviews. Figure 5 below illustrates an example of model inputs, outputs, and calculations.

³ All of the remaining material percentage is no material recovery.

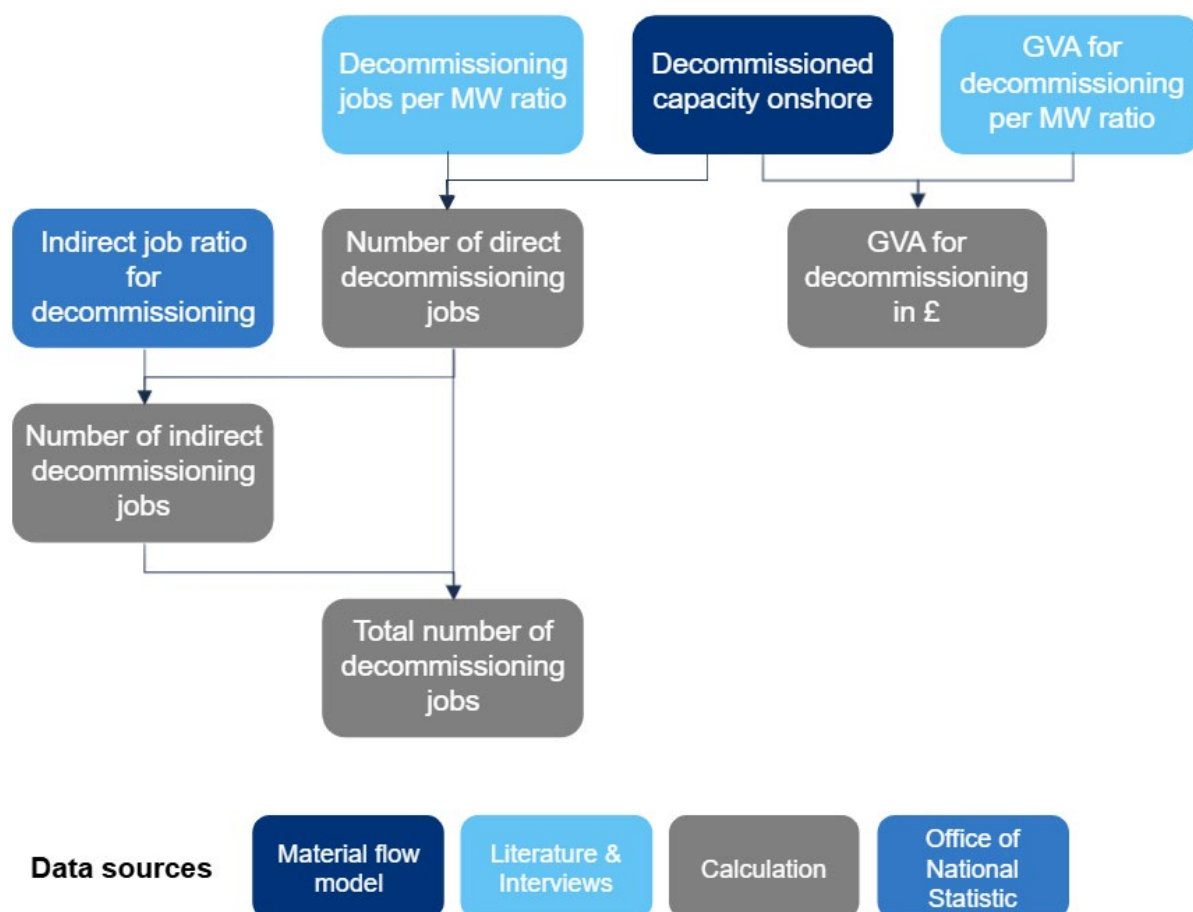


Figure 5: Example calculation process for decommissioning.

A detailed overview of the activities included in the economic modelling is outlined in Appendix C.2 Economic modelling assumptions.

3.1.3.1 Estimate of the Gross Value Added

3.1.3.1.1 Step 1 - Collect Gross Value Added-intensity data

The GVA generated per gigawatt, per tonne, and per number of turbines from repair and recovery activities is determined based on literature reviews and stakeholder interviews.

GVA-intensity ratios for onshore and offshore turbines are presented in Appendix C: Economic impact assessment. The methodology used for evaluating each GVA intensity ratio is explained in the corresponding “Calculation” column. In some instances, multiple ratios have been computed for each activity using different methods and data sources. Where a single value has been selected, the other results have been retained for traceability purposes.

Some of the calculations use GVA multipliers, GVA per Turnover ratio and GVA per FTE Ratio. These GVA multipliers are calculated using a weighted 5-year average spanning from 2019 to 2023. This approach aims to mitigate the influence of short-term fluctuations in the measure. The analysis assumes that the economic impacts of offshore and onshore wind will be comparable to those of broader industries and will remain constant over time. GVA turnover ratios from the ONS are outlined in Table 15 and Table 16.

Table 15: GVA Turnover Ratio (ONS, 2025)

Economic activity	SIC	Industry	GVA turnover ratio
Manufacturing	28.11	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines	20.8%
Repair and refurbishing	33.12	Repair of machinery	51.2%
Repair and refurbishing	33.14	Repair of electrical equipment	56.2%
O&M	35.11	Production of electricity	29.1%
Recycling	38.32	Recovery of sorted materials	24.3%
Transport	49.41	Freight transport by road	45.5%
	52.22	Service activities incidental to water transportation	67.3%
	50.2	Sea and coastal freight water transport	26.6%
Decommissioning	71.12	Engineering activities and related technical consultancy	51.7%
Rental	77.32	Renting and leasing of construction and civil engineering machinery and equipment	56.3%

Table 16: GVA per FTE Ratio (ONS, 2025)

Economic activity	SIC	Industry	GVA per FTE ratio
Recycling	38.32	Recovery of sorted materials	136,088

3.1.3.1.2 Step 2 - Estimate the GVA

The GVA is estimated by multiplying the material flow under consideration in the scenario by the corresponding GVA intensity ratio (i.e. GVA per GW or per tonne).

3.1.3.2 Estimate of the net job impacts

The estimates focus on the direct and indirect job impacts associated with repair and recovery activities from existing wind assets, excluding jobs generated through wider wind sector employment, as per the ONS Low Carbon Renewable Energy Economy (LCREE) survey.

These employment categories (DESNZ, 2025) are defined as:

- Direct jobs: employment that is directly within the primary industry or sector under consideration (for example repair of wind turbines)
- Indirect jobs: employment generated in industries that supply goods or services to the primary sector (including the wider supply chain)

Examples of direct and indirect jobs for repair and recovery activities by the International Renewable Energy Agency (IRENA) are presented in Table 17.

Table 17: Direct and indirect jobs for repair and recovery activities (IRENA, 2017)

Activities	Direct jobs	Indirect jobs
Repair	Onsite and offsite repair or service technician Blade repair technician Engineer	Vessel or crane operator Spare parts manufacturer Vessel manufacturer Repair equipment manufacturer
Refurbishing	<i>Same as above</i>	<i>Same as above</i>
Decommissioning	Construction worker Vessel, crane or truck operator Engineer	Crane manufacturer
Recycling	Dismantling or shredding operator Sorting operator	Recycling equipment manufacturer
Parts and turbines remarketing	Offsite repair or service technician	Spare parts manufacturer

3.1.3.2.1 Step 1 - Collect jobs-intensity ratios

Jobs-intensity ratios per gigawatt, per tonne, and per number of turbines from repair and recovery activities are determined through literature reviews and interviews conducted with sector experts.

Jobs-intensity ratios for onshore and offshore turbines are in Table 73 and Table 74 presented in Appendix C: Economic impact assessment. The calculation method for evaluating each job-

intensity ratio is explained in the “Calculation” column. In some instances, multiple ratios have been computed for each activity using different methods and data sources. If only one result has been selected, the other results have been retained for traceability purposes.

3.1.3.2.2 Step 2 - Estimate the direct employment

The direct employment can be estimated by multiplying the material flow under consideration in the scenario, measured in gigawatt, by the jobs-intensity ratio.

3.1.3.2.3 Step 3 - Estimate the indirect employment

To estimate the indirect employment for onshore wind, this study employed the ratio derived from the “Job estimates for wind generation by 2030 (DESNZ, 2025), which is 1.4 indirect jobs for every 1 direct job. This calculation was based on the ONS LCREE survey’s onshore wind indirect estimates.

To estimate the indirect employment generated by offshore wind, this study combines the direct job estimates with the average ONS type 1 employment multiplier for the years 2019 and 2020. These type 1 multipliers establish a direct link between direct jobs and indirect jobs and are applied to the direct job estimates. Depending on the specific scenario, a direct job can support anywhere from 0.6 to 7.8 indirect jobs.

3.1.3.3 Limitations and uncertainty around jobs and GVA estimates

The estimates presented in this section are subject to significant limitations and uncertainty, reflecting both the diversity of methodological approaches in the literature and the limited availability of robust empirical data. Where possible, the results shown in Section 3.2.5 and 3.2.6 are presented as ranges, to account for the uncertainty and to show the impacts of sensitivity analysis. This demonstrates the impact that the uncertainties have on the jobs and GVA outputs.

- Estimates of jobs and GVA in existing studies exhibit considerable variation. For instance, the cost of decommissioning offshore wind turbines is estimated to range from £150,374 (TNO, 2025) to £482,000 per MW (Adedipe et al., 2020). The number of FTEs required for onshore wind turbine O&M ranges from 56 (Morrison et al., 2024) to 110 (NREL, 2020) per GW.
- Many assumptions are based on modelling rather than empirical evidence, due to the lack of real-world data. This is particularly the case for offshore wind turbine decommissioning, where only a very small number of projects have been carried out in the UK to date.
- The GVA associated with energy generation has not been included in the analysis
- Estimations of GVA and job impact of repair and recovery activities vary significantly per activity (major part replacement, decommissioning, part recovery, material recovery), location (onshore, offshore), turbine capacity, GVA content (UK, non-UK), part (blade, gearbox, generator), and turbine drivetrain technologies (direct-drive, gearbox). Considering all these parameters has not been possible.

A full list of assumptions for the economic modelling is outlined in Appendix C.2 Economic modelling assumptions.

3.1.4 Emissions impact modelling

The emissions modelling focuses on RQ1c, as shown in Table 8, assessing the net impact that life extension has on the emissions produced by onshore and offshore wind assets. This section outlines the methodology used to evaluate the emissions associated with each scenario. An LCA was used to assess the net environmental impact of the lifetime extension of wind assets.

The general process for an LCA is to collect relevant material and activity data, assign appropriate environmental factors, collate the flows of material and energy from the system and report the environmental impacts. It is critical that an LCA also complies with the standardised methodologies used internationally for reporting environmental impacts. The process is governed by the following standards and has been applied to the emissions modelling:

- ISO 14040 - Principles and framework
- ISO 14044 - Requirements and guidelines
- GHG Protocol - Product Life Cycle Accounting and Reporting Standard

3.1.4.1 Emissions scope

For all scenarios, the product system is the UK wind farm fleet delivering energy to the grid. The functional unit is therefore one GWh of electricity delivered to the grid. The scenario definitions that are used in the LCA are outlined in the material flow modelling methodology (3.1.2.2).

The timeline for all onshore emissions modelling is from 1990 until 2070. For offshore scenarios, the timeline is from 2004 until 2065. These timelines ensure that all existing wind farm assets and components replacement have been fully decommissioned and handled. If timelines were restricted until 2050, emissions and credits within the BAU and longer lifetime scenarios are excluded which would have an impact on the final lifetime extension comparison.

3.1.4.1.1 Assessment criteria

The assessment criteria chosen for environmental impact was the average Global Warming Potential over 100 years (GWP100). GWP100 aims to standardise all GHG emissions by converting them to an equivalent mass of Carbon Dioxide (CO₂) emissions. There are many greenhouse gases that contribute to global warming such as CO₂, methane and nitrous oxide. These gases vary in how long they persist in the atmosphere and how powerful an impact they have on global warming per unit mass. GWP100 was selected due to the abundance of available emissions data for a large range of materials and gases. It is also straightforward to understand and communicate as CO₂ is well-understood as a common and significant global warming contributor.

3.1.4.1.2 Material handling allocation method

The avoided burden allocation method was used throughout the emissions impact assessment. This approach assumes that the benefits of recycling are credited to the manufacturing of the primary product. This uses the Allocation at the point of Substitution system model, where the credit from waste-by-products can bring credit into the system for multiple product users. Although this approach is useful to assess the impact of various material handling methods, any benefits from using recycled material during the manufacturing and operations phases are not included.

3.1.4.1.3 System boundary

A system boundary was developed to define which materials and activities will be included, as shown in Figure 6. Life cycle models are used to define which life cycle stages are considered throughout the LCA. There are various life cycle model options, such as:

- Cradle to gate - assesses a product until it leaves the factory gate.
- Cradle to grave – assesses the full product life cycle, from raw material acquisition to EoL material processing.

A life cycle model is chosen based on the required level of detail within the LCA. There are also two main types of LCA methods, attributional and consequential. Attributional LCA assesses the environmental impact of a system by reviewing the flow of materials and energy throughout the system's life cycle. Consequential LCA focuses on how the changes to a system might influence environmental impact. A cradle to grave, attributional life cycle model was used for each scenario.

As discussed in the material flow methodology (3.1.1.2), the in-scope materials for the quantitative modelling are steel, iron, composites and concrete.

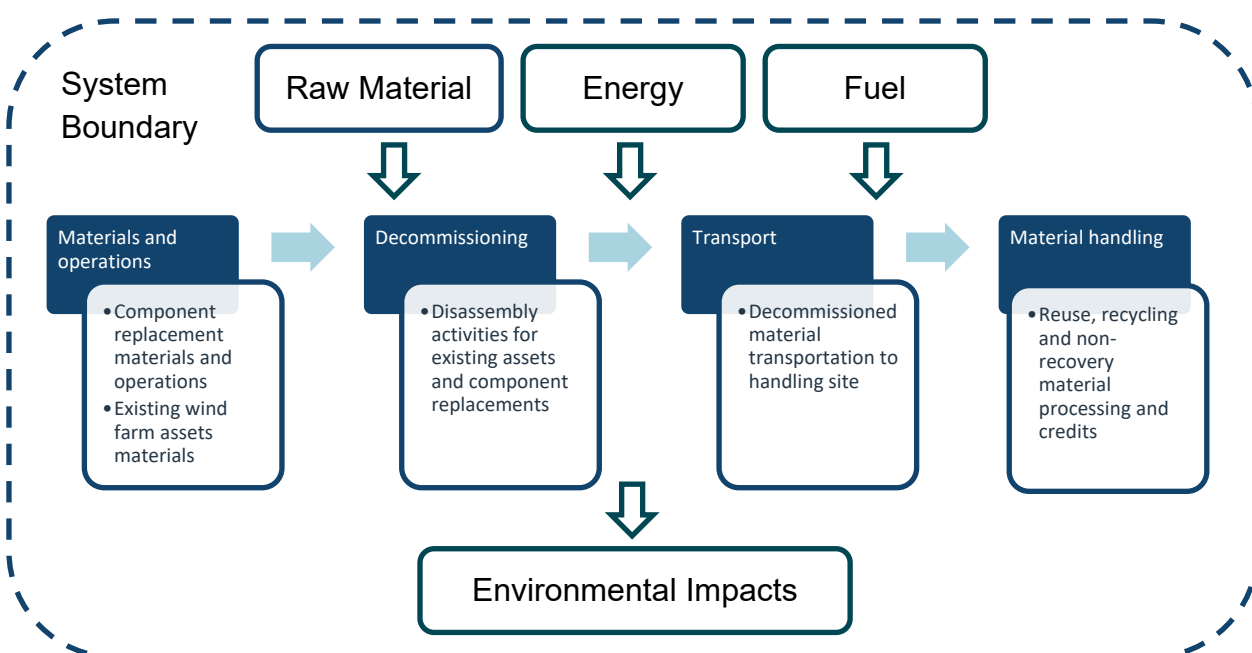


Figure 6: System boundary for the emissions impact assessment.

3.1.4.2 Life cycle inventory

There are two main types of data being considered throughout this LCA:

- Background data – Describes the system environmentally through a collection of emission factors.
- Foreground data - Describes the system technically. This data, also known unit processes, includes information such as materials being used or manufacturing activities.

3.1.4.2.1 Background data

An emissions database was developed considering each life cycle stage as described in Figure 6. Emission factors used within this analysis are taken from various sources and are outlined in Appendix D: Emissions impact assessment. Some key information relating to the emissions data includes:

- The selected system model was the ‘Allocation, cut-off by classification’ to align with the allocation method described in Section 3.1.4.1.2.
- Market activity types were used for all materials, as this includes an average transportation value for transferring raw materials to a manufacturing facility.
- When considering any fuel emissions, Well-to-Wake values were used to ensure all relevant fuel production and combustion stages were considered.

3.1.4.2.2 Foreground data

All material data used within the emissions impact assessment is an input from the material flow analysis. Any other inputs, such as net capacity factors, operational hours and transport distances, are outlined in Appendix D: Emissions impact assessment.

3.2 Results

This section outlines the key findings from the quantitative modelling completed in phase 3. The relevant results for each research question are summarised within separate sections. How each model aligns with the research questions is shown in Table 8. Results have, been separated into onshore and offshore wind.

Throughout each of the results sections, outputs using the baseline and sensitivity modelling assumptions have been included. Due to the various uncertainties and limitations outlined within Section 3.1, the **baseline values should not be considered as the final, correct result. The sensitivity outputs are equally as important and provide valuable context for each RQ conclusion.**

3.2.1 RQ1a: To what extent can repair and maintenance help extend the lifetime of existing wind turbines?

This research question was addressed by the research review and was an input to the material flow model. Overall, empirical data on failure rates, especially for ageing turbines, remains limited. It is widely unknown to which extent repairs and replacements can extend the lifetime of wind turbines, given the influence of multiple factors such as, turbine design, wind conditions, operating strategy, and a lack of practical experience, especially for offshore wind. Consequently, the time of decommissioning was estimated with a Weibull function for the onshore fleet, which was varied across three scenarios. For offshore, the lifetime was estimated by ranging constant lifetime assumptions per offshore wind farm (25-35 years) (see Section 3.1.2.2.1.1).

In addition, given the remaining research gaps and uncertainties of future developments, this study applies constant failure rates per turbine per year (see Section 3.1.2.2.1.2). The scope focused on major replacements of components, as this has the largest impact on labour, costs (Anderson 2024, p. 81, p.106), material use and emissions. Upgrades and partial repowering were not modelled, as these are not currently common practice in the UK.

3.2.2 RQ1b: What is the net impact on material demand associated with extending the lifetime of wind assets?

The material demand associated with extending the lifetime of wind assets considered in this analysis is the material demand for installing wind turbines, including foundations, along with component replacements of blades, gearboxes and generators during O&M activities. The materials in scope are concrete, steel and iron, and composites. The net impact is derived by putting the material demand (t) in relation with the total energy generation (GWh) over the assets' lifetime. It should be noted that any reductions in material demand due to the use of second-lifecycle components is accounted for in RQ2a and not in RQ1b to avoid double-counting of impacts.

The following shows the results for the BAU, shorter lifetime and longer lifetime scenarios for the onshore (3.2.2.1) and offshore wind turbine fleet in the UK (3.2.2.2).

3.2.2.1 Onshore wind

The total material demand for installing onshore wind turbines (including foundations) until 2027 remained constant across all lifetime scenarios, as future installation were out of scope. The total installation material demand for each material is:

- Concrete: 9.9 Mt
- Steel and iron: 2.7 Mt
- Composites: 0.2 Mt

To put the total masses into perspective, Figure 7 presents the yearly installations and the associated material demand of concrete (orange bar), steel and iron (green bar) and

composites (blue bar). It shows that annual installation rates vary over the last decades, peaking in 2017, and that concrete is the material in scope contributing the most to the total material demand for annual installations, followed by steel & iron, and then composites.

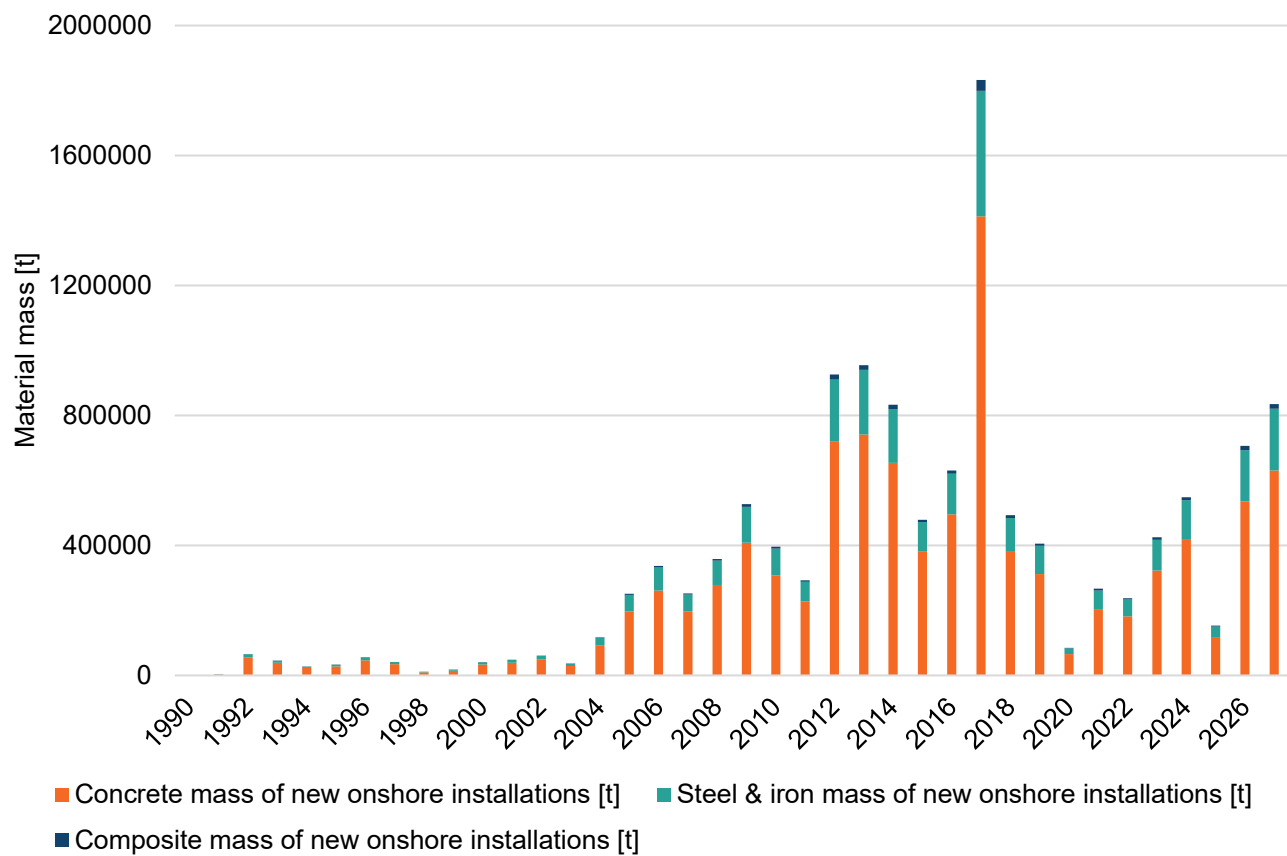


Figure 7: Material demand in tonnes for new onshore wind turbine installations from 1990 until 2027.

Table 18 shows the total material demand for component replacements during operation and maintenance at onshore wind sites. Compared with new installations, the material demand for component replacements is lower, however it is still a significant contributor of the total material demand (17-22%, depending on lifetime scenario).

Table 18: Total onshore wind material demand in tonnes for component replacements from 1990 until 2050 and 2070⁴.

Scenario	Steel and Iron (tonnes)		Composite (tonnes)	
	2050	2070	2050	2070
BAU	602,494	615,441	137,914	145,359
Shorter	483,679	484,799	113,693	114,525
Longer	631,089	652,769	143,238	154,169

As shown in Table 18, material demand is highest for the longer lifetime and lowest for the shorter lifetime. This is due to a longer lifetime of the fleet and hence continued material demand for component replacements.

Material demand for component replacements increases further when extending the timeline from 2050 to 2070, as the model applies annual replacement rates over the full lifetime of the assets. However, the magnitude of this increase varies by material and lifetime scenario. For steel and iron, material demand only increases by 0.2% for shorter lifetime compared to 3.4% for longer lifetime. Similarly for composites, material demand only increases by 0.7% for shorter lifetime compared to 7.6% for longer lifetime. As demonstrated in Figure 8, Figure 9 and Figure 10 this is due to the majority of replacements being completed by 2050 for the shorter lifetime. Replacements are still being completed during the longer lifetime until approximately 2065.

⁴ Component replacements are from generators, gearboxes and blades, hence no concrete is included.

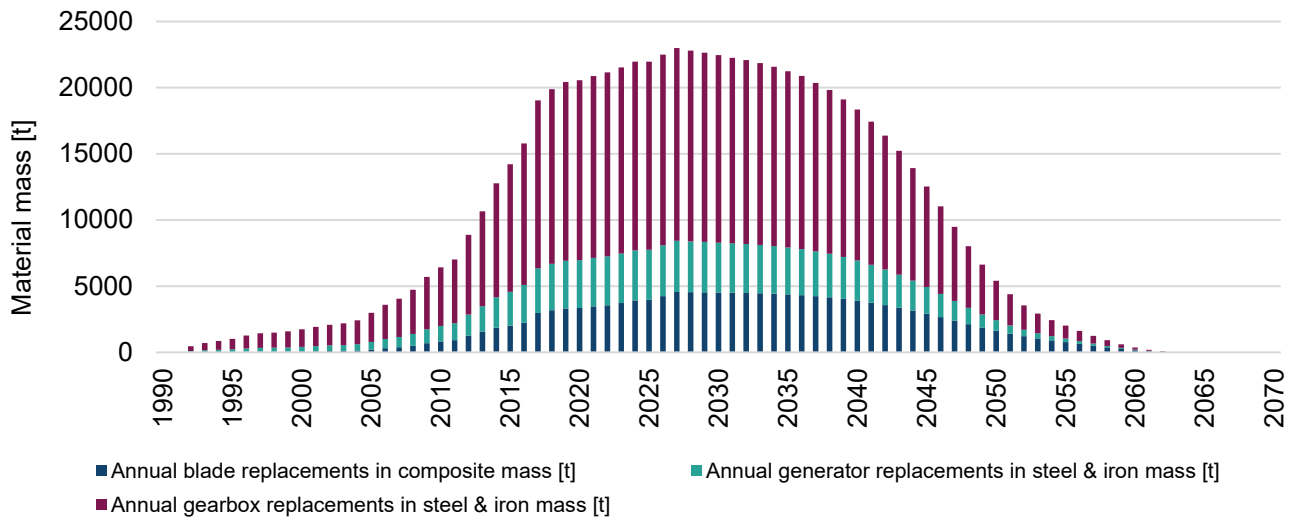


Figure 8: Onshore wind BAU lifetime scenario annual component replacement material mass (1990 – 2070).

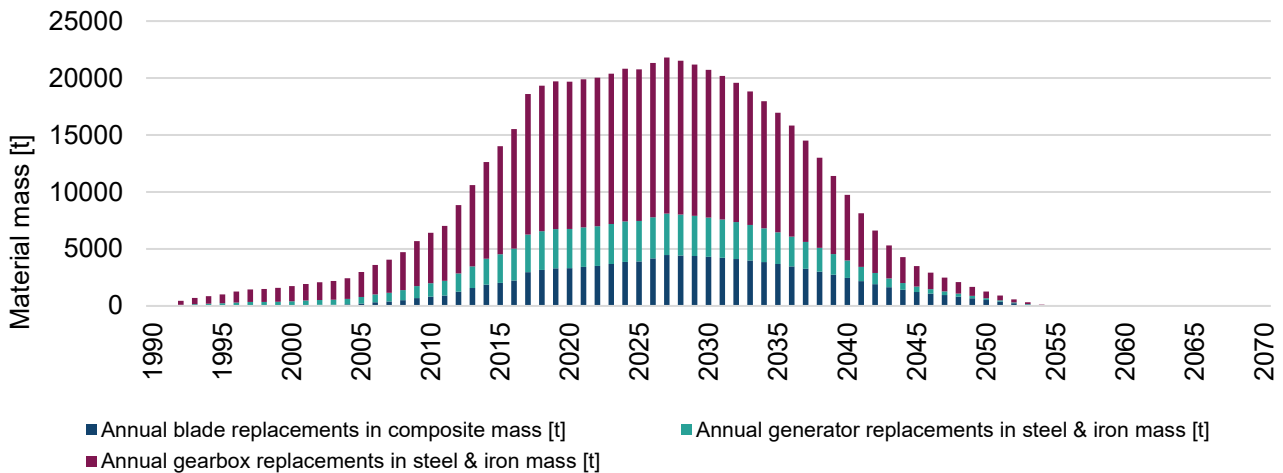


Figure 9: Onshore wind shorter lifetime scenario annual component replacement material mass (1990 – 2070).

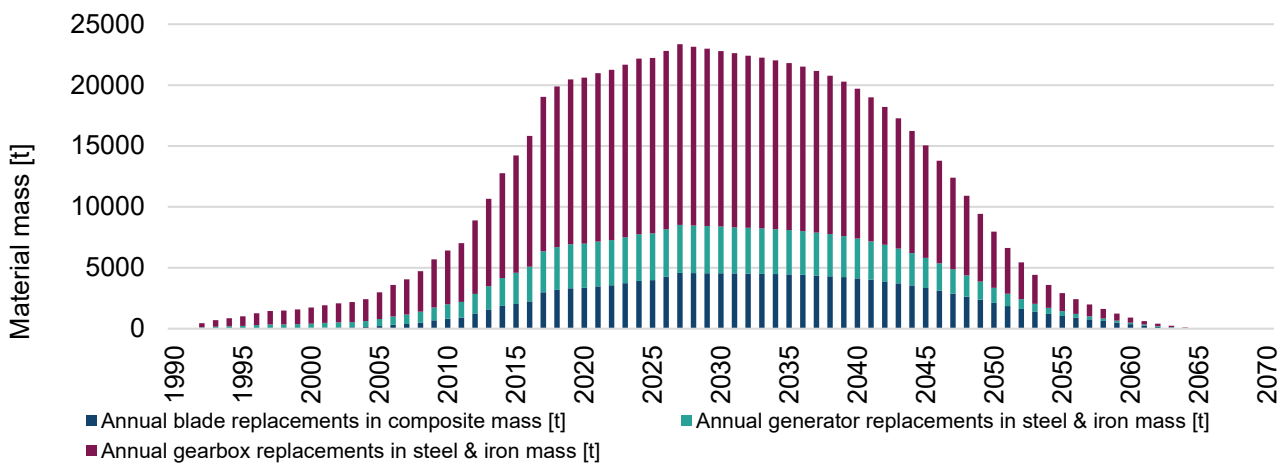


Figure 10: Onshore wind longer lifetime scenario annual component replacement material mass (1990 – 2070).

When assessing the net impact of lifetime extension on material demand for onshore wind assets, material use must be considered relative to energy generation. Extending the operational lifetime increases total energy output, thereby reducing the material intensity of generation. Table 19 outlines the total onshore wind material demand against the energy generation for each scenario. The total timeline data from 1990 until 2070 was used for this comparison, to capture the complete material demand and energy generation for each scenario. The existing wind farm installation material demand was also included in addition with the component replacements. This was required, as the generated energy is produced from a combination of the existing wind farms and the replacements required to sustain operation (including life extensions).

Table 19: Total onshore wind material demand for installation and component replacements per energy generation (1990 to 2070).

Scenario	Total mass (Mt)	Energy generation (GWh)	Tonnes per GWh
BAU	13.6	1,267,474	10.73
Shorter	13.4	996,282	13.45
Longer	13.6	1,333,990	10.15

As shown in Table 19, when the total energy generation per lifetime scenario is taken into account, **the longer lifetime scenario has the lowest material demand per energy generated, followed by the BAU scenario and then the shorter lifetime scenario.** From short to long lifetime, total installation and component replacement material demand increases by 1.5%, while energy generation increases by 34.1%. Although more material is required, the increase in energy generation is enough to offset the material demand.

Using the replacement rate ranges shown in Table 11, a sensitivity analysis of material demand based on a minimum and maximum replacement rates is shown in Table 20. As outlined in section 3.1.2.2.1.2, replacement rates for gearboxes and generators stated in literature significantly vary, resulting to a wide range when comparing the minimum and maximum masses for steel and iron.

Table 20: Onshore wind material demand sensitivity analysis for a minimum and maximum replacement rates (1990 – 2070).

Scenario	Total component replacement material mass (tonnes)			
	Minimum		Maximum	
	Steel and iron	Composites	Steel and iron	Composites
BAU	362,348	132,145	1,165,379	151,966
Shorter	285,414	104,114	918,227	119,731
Longer	384,239	140,153	1,235,991	161,176

When comparing the minimum replacement scenario to the baseline for onshore wind, total material demand decreases by up to 41.5% for steel and iron, and up to 9.2% for composites. For the maximum replacement scenario, there is an increase of up to 88.3% for steel and iron, and 4.5% for composites. Regardless of the sensitivity, **the longer lifetime scenario remains the most effective, maintaining the lowest material demand per energy generation.**

3.2.2.2 Offshore wind

The total material demand for installing offshore wind turbines (including foundations/substructures) until 2027 remained constant across all scenarios, as future installation were out of scope. The total installation material demand for each material under scope of this study is:

- Concrete: 0.03 Mt, in wind project ‘Blyth Offshore Demonstrator phase 1’
- Steel and iron: 10.7 Mt
- Composites: 0.4 Mt

To put the total masses into perspective, Figure 11 shows the annual installations and the associated material demand of concrete (orange bar), steel & iron (green and purple bars), and composites (blue bar). It shows that annual installation rates have varied over recent decades with the first installation in 2004, and peaking with the material demand associated with wind farms expected to be fully commissioned in 2027. In contrast to onshore wind, steel represents the dominant material contribution to total demand for new offshore installations, followed by composites, and a negligible mass of concrete.

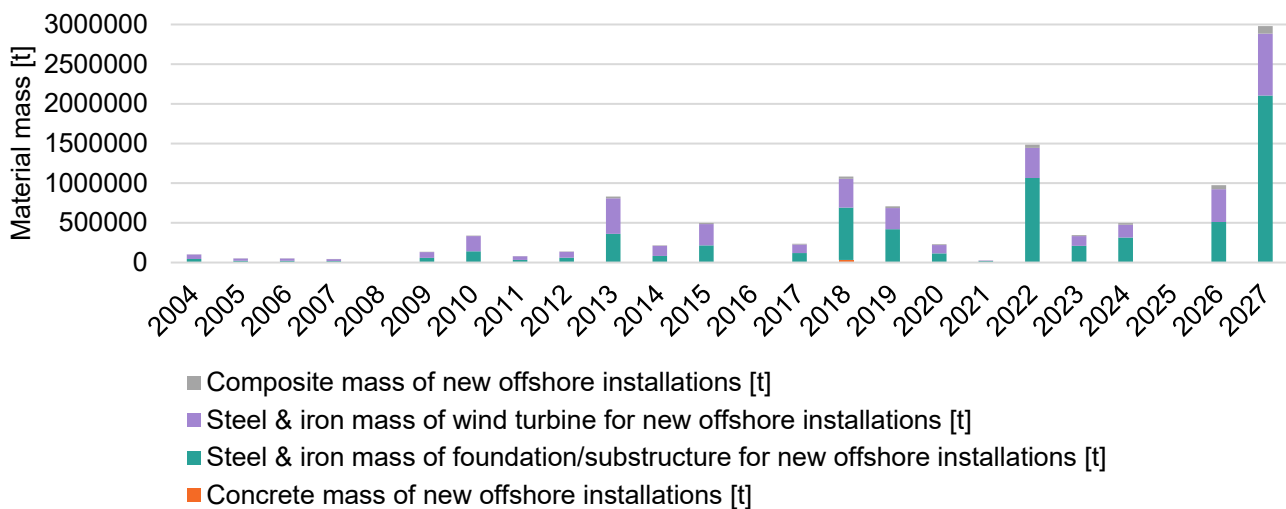


Figure 11: Material demand in tonnes for new offshore wind turbine installations from 2004 until 2027.

Table 21 shows the total material demand for component replacements during O&M at offshore wind sites. Compared with new installations, the material demand for component replacements is lower, however it is still a significant contributor of the total material demand (14-19%, depending on lifetime scenario).

Table 21: Total offshore wind material demand in tonnes for component replacements from 2004 until 2050 and 2070.

Scenario	Steel and Iron (tonnes)		Composite (tonnes)	
	2050	2070	2050	2070
BAU	543,697	571,440	290,865	319,700
Shorter	473,691	476,199	263,550	266,417
Longer	592,713	666,680	305,537	372,983

Similarly to the onshore results in Section 3.2.2.1, the material demand is highest for the longer lifetime and lowest for the shorter lifetime, as shown in Table 21. Due to the increase in component replacements, more material is required to deliver the life extension. Material demand for component replacements increases further when extending the timeline from 2050 to 2070. However, steel and iron material demand only increases by 0.53% for shorter lifetime but by 12.5% for longer lifetime. Similarly for composites, material demand only increases by 1.1% for shorter lifetime but by 22.1% for longer lifetime. As demonstrated in Figure 12, Figure 13 and Figure 14 this is due to the majority of replacements being completed by 2050 for the shorter lifetime. Replacements are still being completed during the longer lifetime until approximately 2060.

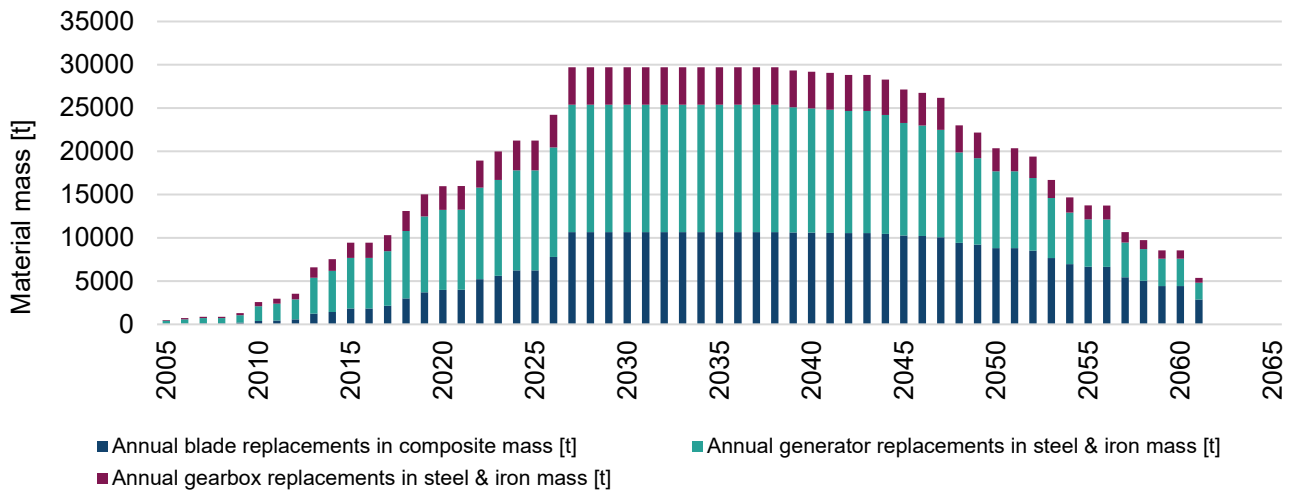


Figure 12: Offshore wind longer lifetime scenario annual component replacement material mass (2004 – 2065).

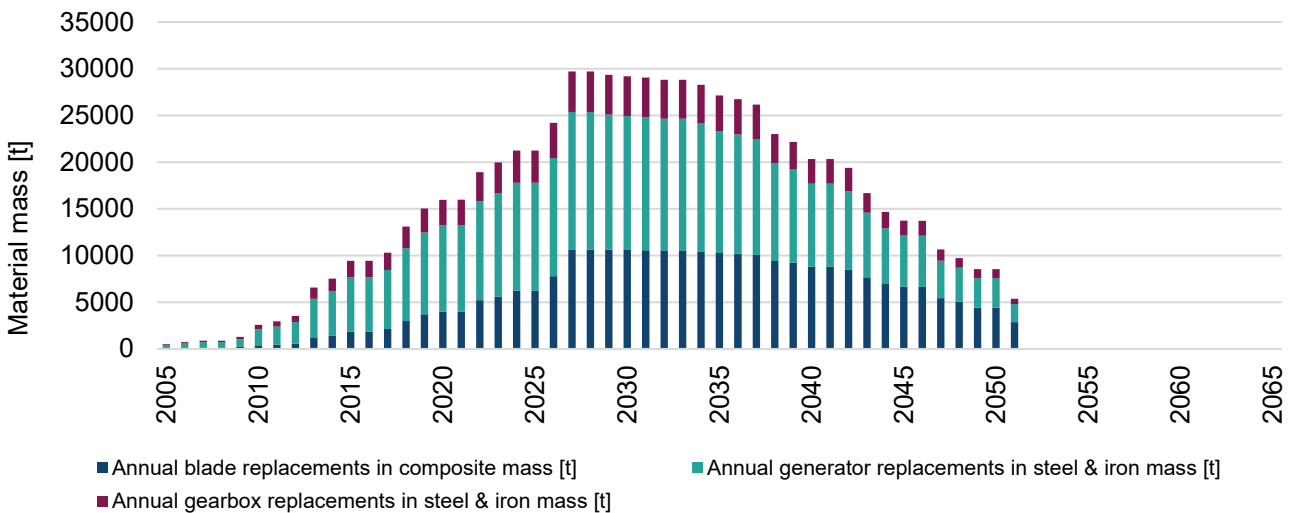


Figure 13: Offshore wind shorter lifetime scenario annual component replacement material mass (2004 – 2065).

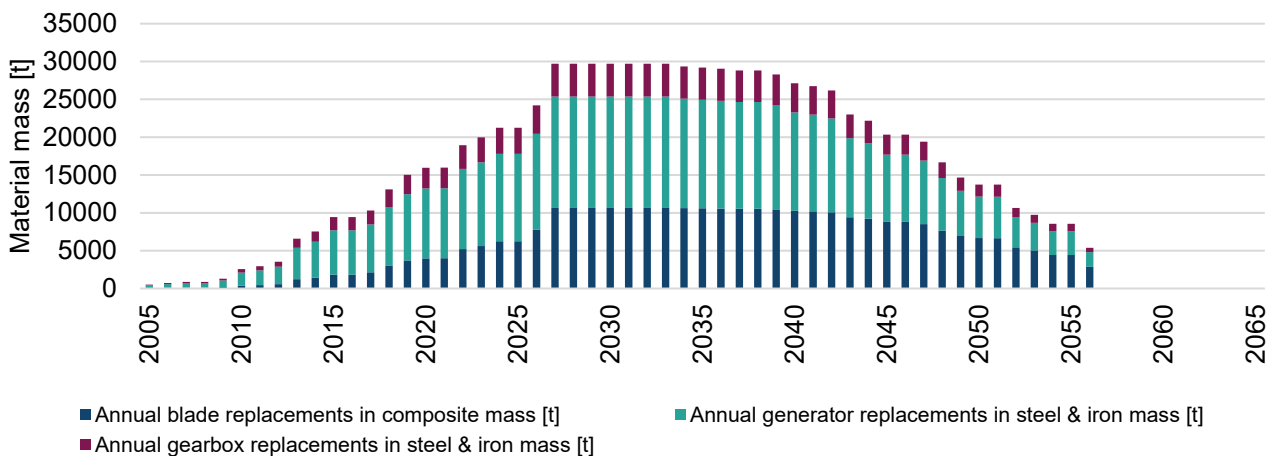


Figure 14: Offshore wind BAU scenario annual component replacement material mass (2004 – 2065).

As in the case of onshore wind in Section 3.2.2.1, the total material demand for offshore wind also needs to be considered in terms of energy generation. Table 22 outlines the total offshore wind material demand against the energy generation for each scenario. The total timeline data from 2004 until 2070 was used for this comparison, to capture the complete material demand and energy generation for each scenario. The existing wind farm installation material demand was also included in addition with the component replacements.

Table 22: Total offshore wind material demand for installation and component replacements per energy generation (2004 to 2065).

Scenario	Total mass (Mt)	Energy generation (GWh)	Tonnes per GWh
BAU	11.9	2.66×10^6	4.49
Shorter	11.8	2.22×10^6	5.32
Longer	12.1	3.1×10^6	3.90

As shown in Table 22, when the increased energy generation of life extension is taken into account, **the longer lifetime scenario has the lowest material demand per energy generated, followed by BAU and then shorter lifetime**. From short to long lifetime, total installation and component replacement material demand increases by 1.5%, while energy generation increases by 39.6%. Although more material is required, the increase in energy generation is enough to offset the material demand.

Using the replacement rate ranges shown in Table 11, a sensitivity analysis of material demand based on a minimum and maximum replacement rate is shown in Table 23.

Table 23: Offshore material demand sensitivity analysis for a minimum and maximum replacement rates (2004 until 2065).

Scenario	Total component replacement material mass (tonnes)			
	Minimum		Maximum	
	Steel and iron	Composites	Steel and iron	Composites
BAU	60,869	213,133	1,814,694	426,266
Shorter	50,570	177,611	1,512,291	355,222
Longer	71,168	248,655	2,117,096	497,311

When comparing the minimum replacement scenario to the baseline for offshore wind, total

material demand decreases by up to 89.4% for steel and iron, and up to 33.3% for composites. For the maximum replacement scenario, there is an increase of up to 217.6% for steel and iron, and 33.3% for composites. Regardless of the sensitivity, **the longer lifetime scenario remains the most effective, maintaining the lowest material demand per energy generation.**

For both onshore and offshore wind, material demand per energy generation reduces as lifetime is extended. For all of the replacement rate sensitivities, the longer lifetime remained the most effective scenario. Moreover, improved O&M practices (e.g. predictive maintenance) as well as incentivising reliable product design for future installations may positively impact material demand across the lifetime scenarios, in case it reduces replacement efforts.

3.2.3 RQ1c: What is the net impact on emissions associated with extending the lifetime of existing onshore and offshore wind assets?

3.2.3.1 Onshore wind

To capture the impact of the full material mass flow for every lifecycle stage, a timeline from 1990 until 2070 has been used for all scenarios. Figure 15 compares the total emissions impact of each life cycle between scenarios. This uses the baseline replacement and handling ratios from the material flow modelling (3.1.2).

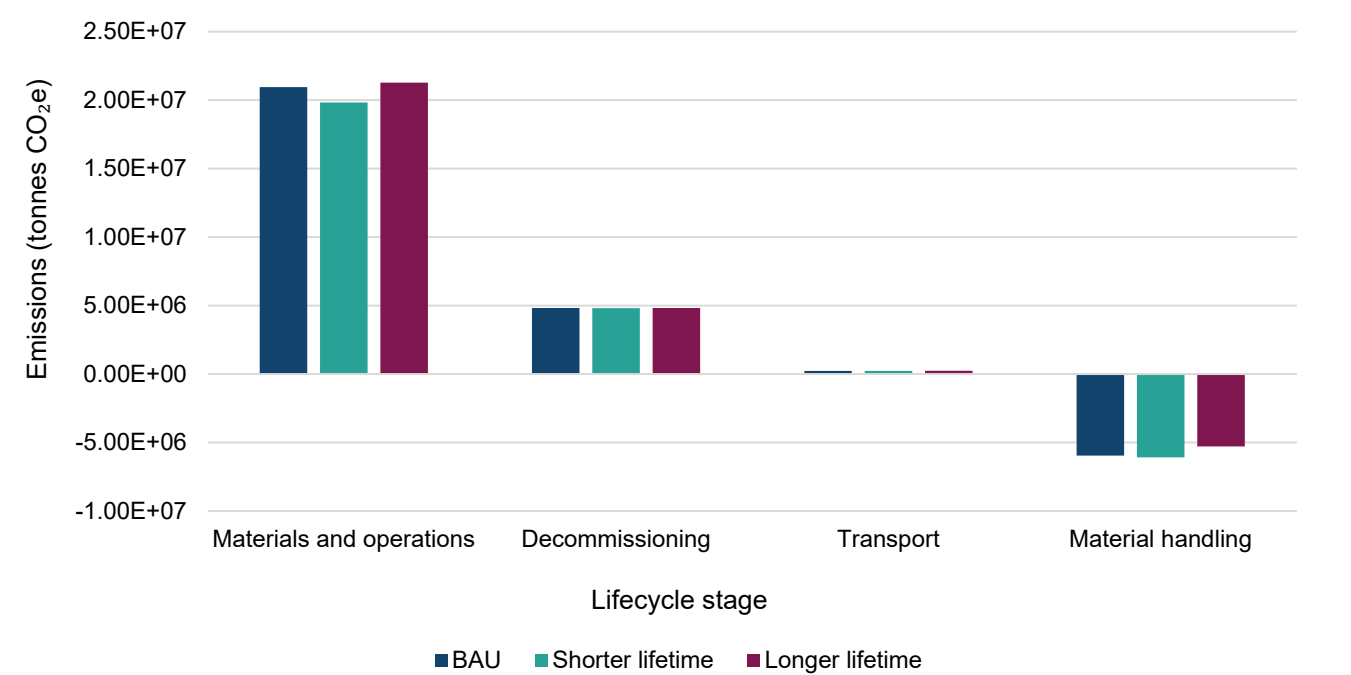


Figure 15: Onshore wind emissions per lifecycle stage for each scenario (1990 – 2070).

As shown in Figure 15, the longer lifetime scenario produces the highest emissions for materials and operations, decommissioning, and transport, followed by BAU and then shorter lifetime. The largest variation between scenarios occurs in the materials and operations stage, with emissions increasing 7.6% from the shorter and longer lifetime. Over the same range, decommissioning and transport emissions also increase by 0.2% and 3.9%, respectively. These differences are due to the increased material demand for component replacement for

both longer lifetime and BAU when compared to shorter lifetime. This has an impact on all lifecycle stages as the materials are decommissioned, transported and then handled.

Using the baseline material handling values outlined in Table 14, the credits from material handling is highest for shorter lifetime, followed by BAU and then longer lifetime. Although more material is being handled, less overall material is sent for reuse when considering the baseline handling ratios. This results in a 14.9% decrease in material handling credits for the longer lifetime when compared to the shorter lifetime.

When considering the net impact on emissions associated with extending the lifetime of onshore wind assets, the demand also needs to be considered in terms of energy generation. Due to the increased lifetime, energy generation also increases and reduces the net impact on emissions. Table 24 shows the total emissions per energy generation for each scenario.

Table 24: Onshore wind total emissions per energy generation for each scenario (1990 – 2070).

Scenario	Total emissions (tonnes CO ₂ e)	Energy generation (GWh)	Tonnes CO ₂ e per GWh
BAU	2.01×10^7	1.27×10^6	15.82
Shorter	1.88×10^7	9.99×10^5	18.82
Longer	2.10×10^7	1.34×10^6	15.65

As shown in Table 24, when considering energy generation per scenario, the longer lifetime produces the lowest emissions per energy generation, followed by BAU and then shorter lifetime. Although more materials and operations are required for the increased component replacements in the longer lifetime, the increased energy generation is enough to offset this when considering the baseline replacement and handling ratios.

The impact of varying the potential reuse ratios for each scenario is shown in Figure 16.

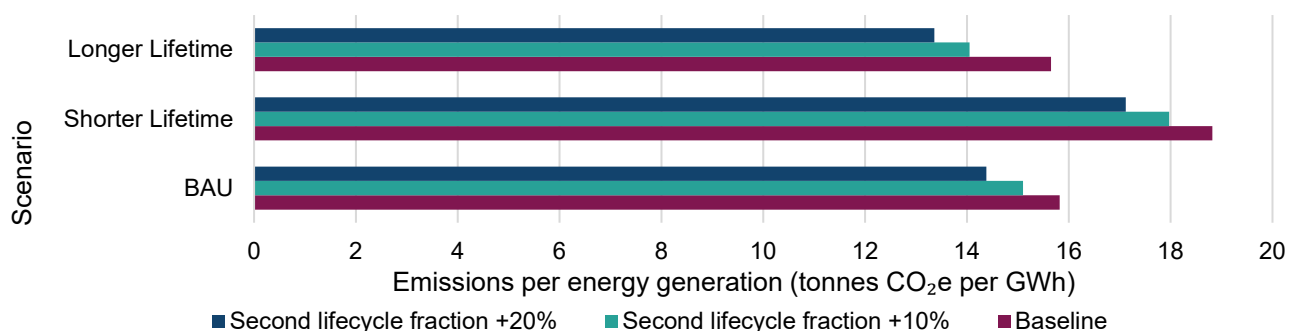


Figure 16: Onshore total emissions per energy generation sensitivity analysis for varying second lifecycle fraction (1990 – 2070).

Increasing the material reuse fraction reduces total emissions per energy generation for all scenarios (Figure 16). This variation has the largest impact on longer lifetime (14.6% reduction), followed by BAU (9.1% reduction) and then shorter lifetime (9% reduction). As the reuse fraction increases across all scenarios, the relative ranking remains unchanged compared to the baseline assumptions.

Table 25 shows the impact that component replacement ratios have on the total emissions per energy generation, using the minimum and maximum values outlined in Table 11.

Table 25: Onshore total emissions per energy generation sensitivity analysis for a minimum and maximum component replacement rate (1990 – 2070).

Scenario	Tonnes CO ₂ e per GWh	
	Minimum replacement rate	Maximum replacement rate
BAU	15.16	16.95
Shorter	18.18	19.92
Longer	14.06	15.92

As in the case of the reuse fraction sensitivities, the longer lifetime remains the lowest emissions per energy generation for both the minimum and maximum replacement ratios. This is followed by the BAU and then the shorter lifetime scenario. The percentage increase from the minimum to maximum replacement ratios is largest for the longer lifetime (13.3%), followed by BAU (11.8%), and then shorter lifetime scenario (9.6%).

When considering the variation of material recovery ratios per material, composites and concrete have minimal impact. As composite material recovery increases from 0% to 100%, the total emissions per energy generation increases by 0.1% for shorter lifetime and 0.2% for longer lifetime. This increase is attributed to the assumption that the recovered composite material is mechanically ground and reused in construction applications, where the avoided carbon burden (credit) is smaller than the emissions generated by the mechanical recovery process itself. Different composite reprocessing technologies will result in different emissions outputs. For concrete material recovery, as ratio increases from 0% to 100%, the total emissions per energy generation decreases by 0.1% for shorter lifetime and by 0.07% for longer lifetime.

However, steel and iron material recovery has a significant impact on the model outputs. As the recovery ratio increases from 5% to 75%, the total emissions per energy generation decrease by 8.8% for shorter lifetime and 12.5% for longer lifetime, owing to the emissions benefits associated with the use of recycled steel compared to virgin material.

3.2.3.2 Offshore wind

To capture the impact of the full material mass flow for every lifecycle stage, a timeline from 2004 until 2065 has been used for all scenarios. Figure 17 compares the total emissions impact of each life cycle between scenarios. This uses the baseline replacement and material handling ratios outlined in Table 14.

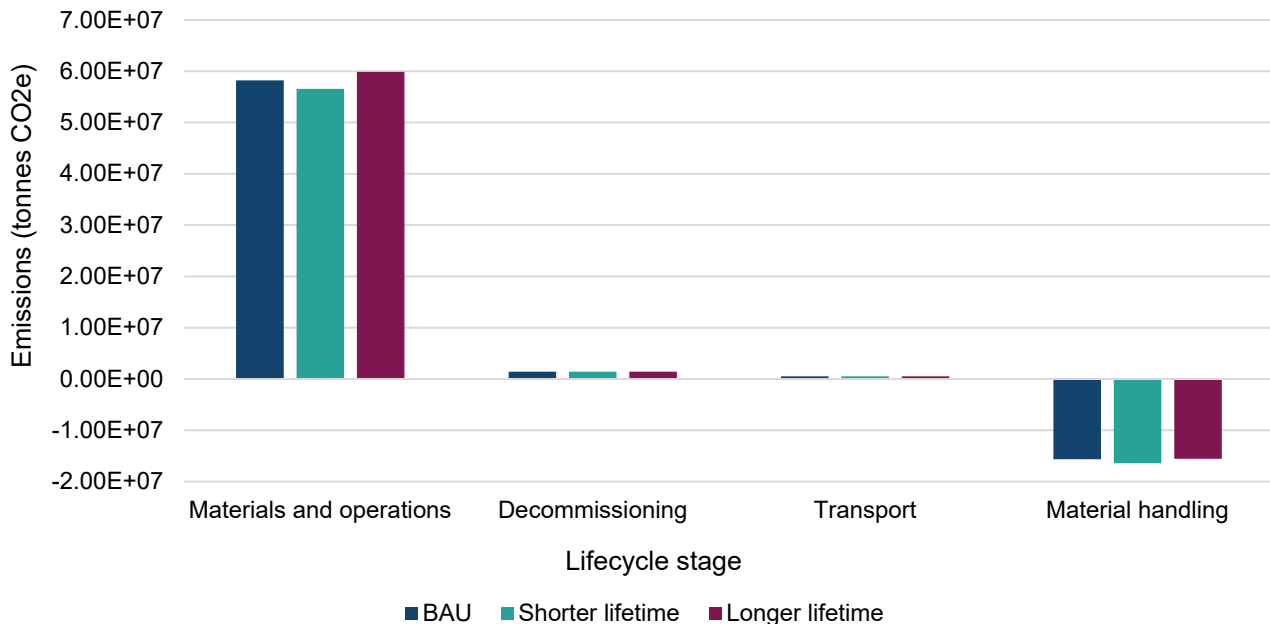


Figure 17: Offshore wind emissions per lifecycle stage for each scenario (2004 – 2065).

As shown in Figure 17, the longer lifetime scenario produces the highest emissions for materials and operations, decommissioning, and transport, followed by the BAU scenario and then the shorter lifetime scenario. The difference between scenarios is the highest for materials and operations, with a 5.8% increase between shorter to longer lifetime. Between shorter to longer lifetime, decommissioning and transport emissions also increase by 0.2% and 2.3%, respectively.

Using the baseline material handling values, the credits from material handling is highest for shorter lifetime, followed by BAU and then longer lifetime. Although more material is being handled, less overall material is sent for reuse when considering the baseline handling ratios. This results in a 4.9% decrease in material handling credits for the longer lifetime when compared to the shorter lifetime.

When considering the net impact on emissions associated with extending the lifetime of onshore wind assets, the demand also needs to be considered in terms of energy generation. Due to the increased lifetime, energy generation also increases and reduces the net impact on emissions. Table 26 shows the total emissions per energy generation for each scenario.

Table 26: Offshore wind total emissions per energy generation for each scenario (2004 – 2065).

Scenario	Total emissions (tonnes CO ₂ e)	Energy generation (GWh)	Tonnes CO ₂ e per GWh
BAU	4.45×10^7	2.66×10^6	16.74
Shorter	4.21×10^7	2.22×10^6	18.98
Longer	4.63×10^7	3.10×10^6	14.92

As shown in Table 26, when taking into account energy generation per scenario, the longer lifetime produces the lowest emissions per energy generation, followed by BAU and then shorter lifetime.

The impact of varying the reuse ratios for each scenario is shown in Figure 18.

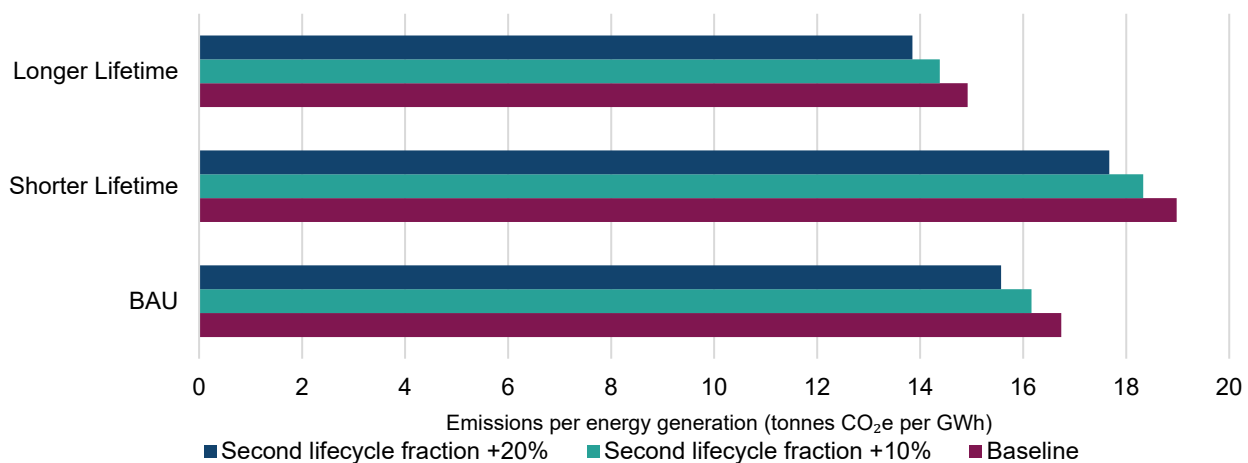


Figure 18: Offshore total emissions per energy generation sensitivity analysis for varying second lifecycle fraction (2004 – 2065).

Increasing the reuse fraction reduces total emissions per energy generation for all scenarios (Figure 18). This variation has the largest impact on longer lifetime (7.2% reduction), followed by BAU (7% reduction) and then shorter lifetime (6.9% reduction). As the reuse fraction increases across all scenarios, the relative ranking remains unchanged compared to the baseline assumptions.

Table 27 shows the impact that component replacement ratios have on the total emissions per energy generation, using the minimum and maximum values outlined in Table 11.

Table 27: Offshore total emissions per energy generation sensitivity analysis for a minimum and maximum component replacement rates (2004 – 2065).

Scenario	Tonnes CO ₂ e per GWh	
	Minimum replacement rate	Maximum replacement rate
BAU	15.55	18.63
Shorter	17.60	20.44
Longer	13.80	17.00

As in the case of the reuse fraction sensitivities, the longer lifetime remains the lowest emissions per energy generation for both the minimum and maximum replacement ratios. This is followed by the BAU and then the shorter lifetime scenario. The percentage increase from the minimum to maximum replacement ratios is largest for the longer lifetime (23.2%), followed by BAU (19.8%), and then shorter lifetime (16.1%)

When considering the variation of material recovery ratios per material, composites and concrete have minimal impact. As composite material recovery increases from 0% to 100%, the total emissions per energy generation increases from 0.11% for shorter lifetime and 0.2% for longer lifetime, again owing to the assumption that the recovered mechanically ground materials will be used in construction applications. Concrete material recovery sensitivities were excluded due to the negligible material mass for offshore wind.

However, steel and iron material recovery has a significant impact on the model outputs. As the recovery ratio increases from 5% to 75%, the total emissions per energy generation decrease by 17.4% for shorter lifetime and 16.8% for longer lifetime.

3.2.4 RQ2a: How much material and reusable components can be recovered from existing onshore and offshore wind assets?

Referring to the results from RQ1b, the total material to be handled stems from the expected decommissioning of the installed wind assets as well as from component replacements during O&M activities. Three handling pathways are considered: i. turbine and component reuse, ii. material recovery and iii. no recovery for the materials in scope (i.e. concrete, steel & iron and blade composites).

The estimated quantities for recovery of materials and reusable components and turbines are a portion of the material used for installing wind turbines, including foundations, along with component replacements of blades, gearboxes and generators.

To answer RQ2a, the following shows the results for the BAU, shorter lifetime and longer lifetime scenarios for the onshore (3.2.4.1) and offshore wind turbine fleet in the UK (3.2.4.2).

3.2.4.1 Onshore wind

The total mass of material, including decommissioning of installed onshore wind turbines and replacement of components, produced from each scenario is shown in Table 28, assuming 100% removal of the foundation.

Table 28: Onshore total mass of material handled from each scenario from 1990 until 2050 and 2070.

Scenario	Total material mass (Mt)
Material timeline final year	2070
BAU	13.6
Shorter	13.4
Longer	13.6

Similarly to Section 3.2.2, significant material mass is excluded from the analysis when the timeline is restricted to 2050, especially for longer lifetime and BAU scenarios. Approximately 5.5 Mt and 4.2 Mt are excluded from the longer and BAU scenarios respectively, while only 1.4 Mt are missed from the shorter lifetime.

Figure 19, Figure 20 and Figure 21 show the annual material handling mass values for each scenario, split into turbine and component reuse (second lifecycle), material recovery and no recovery. These figures further demonstrate the impact of timeline on the total material mass. The shorter lifetime is fully handled before 2060, while longer lifetime is still being handled up until approximately 2070.

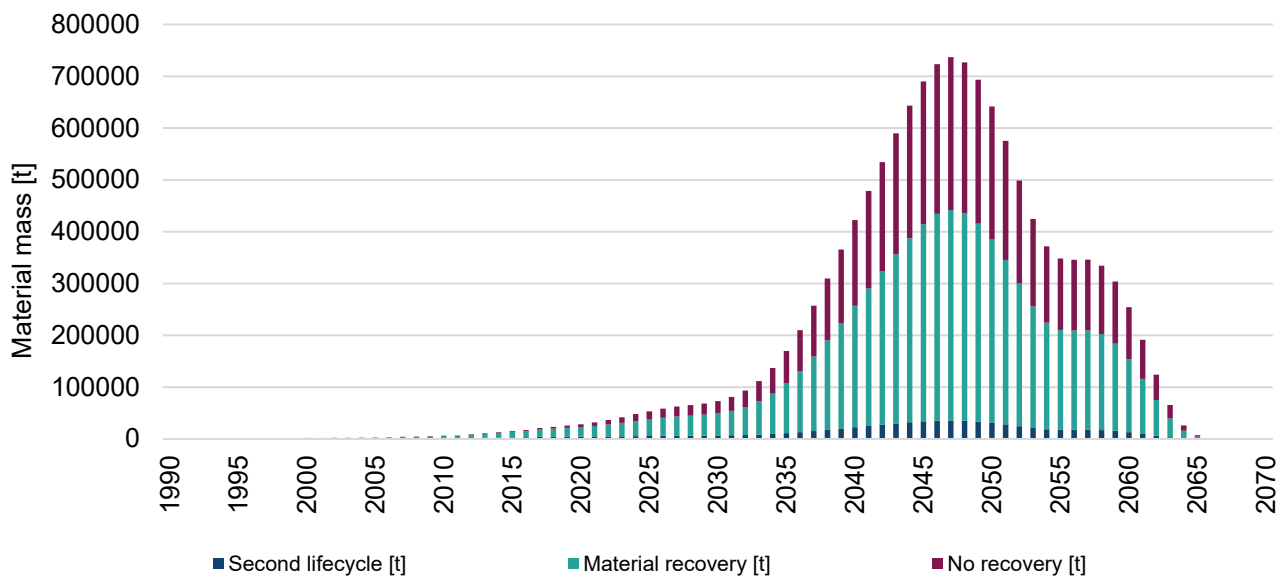


Figure 19: Onshore wind BAU lifetime scenario annual material handling following decommissioning and replacements of blades, generators and gearboxes during operation (1990 – 2070).

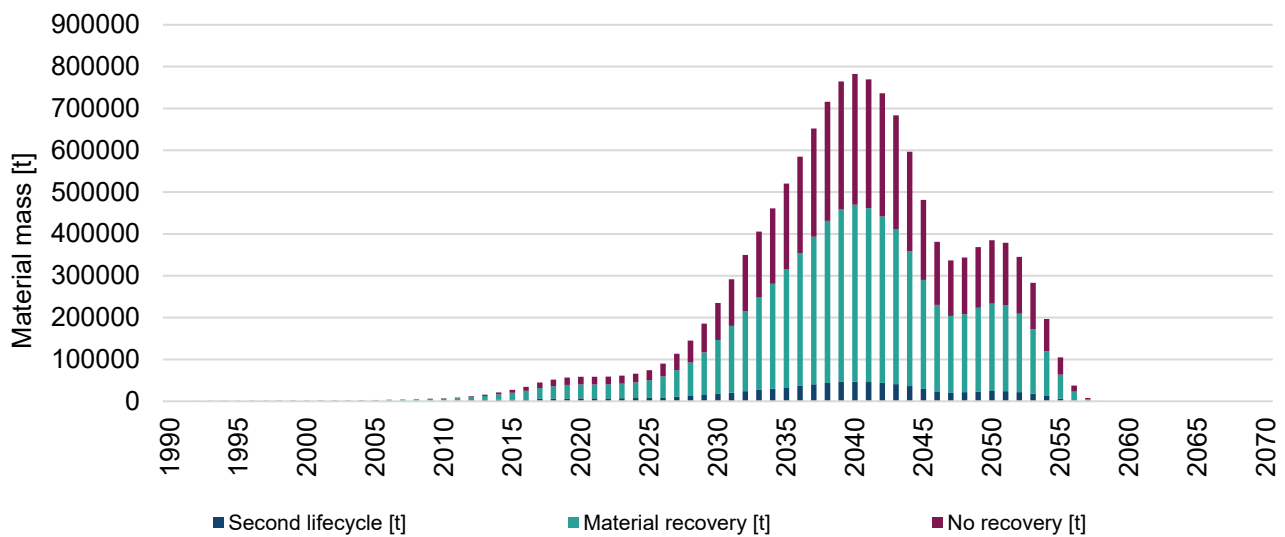


Figure 20: Onshore wind shorter lifetime scenario annual material handling following decommissioning and replacements of blades, generators and gearboxes during operation (1990 – 2070).

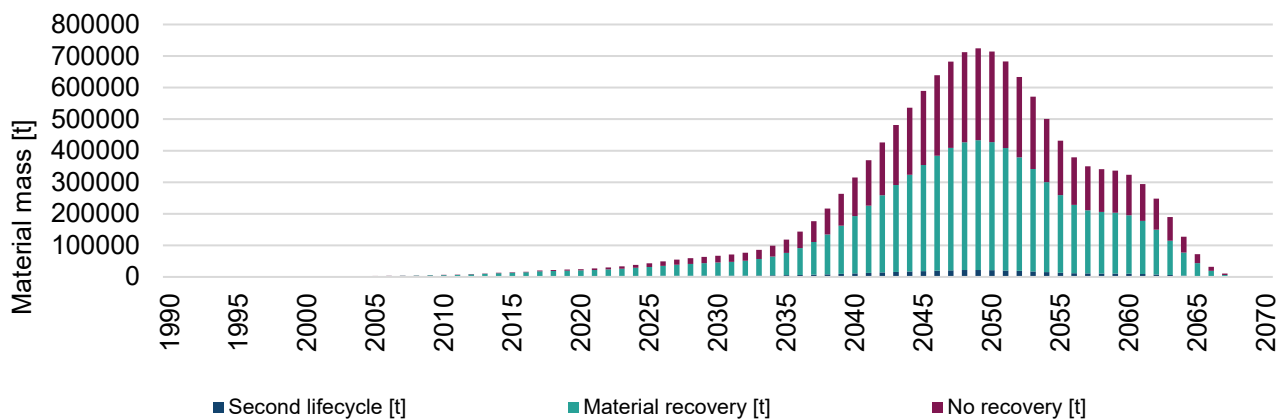


Figure 21: Onshore wind longer lifetime scenario annual material handling following decommissioning and replacements of blades, generators and gearboxes during operation (1990 – 2070).

The total material handling mass values from each scenario is a combination of the installed wind farm assets and the component replacements throughout the total lifetime. Figure 19, Figure 20 and Figure 21 show the differences in reuse, recovery and no recovery, respectively, for each scenario. The material handling ratios are based on the values outlined in Section 3.1.2.2.2.

3.2.4.1.1 Reuse

Reuse occurs in form of reusing the entire turbine, components or parts. At this stage, a detailed estimation of each second-hand stream is not feasible, and hence constant reuse fractions per scenario were applied (see Section 3.1.2.2.2), underlying the importance of also considering the sensitivity results.

Figure 22 outlines the total estimated reuse for each scenario in onshore wind, expressed in steel & iron mass and composite mass. Concrete is not expected to be reused, as only present in the foundation. The differences between steel & iron masses and composite masses shown in Figure 22 are solely because a larger proportion of the wind turbine's total mass is accounted for by steel & iron. When further research becomes available, future studies can model this in more detail.

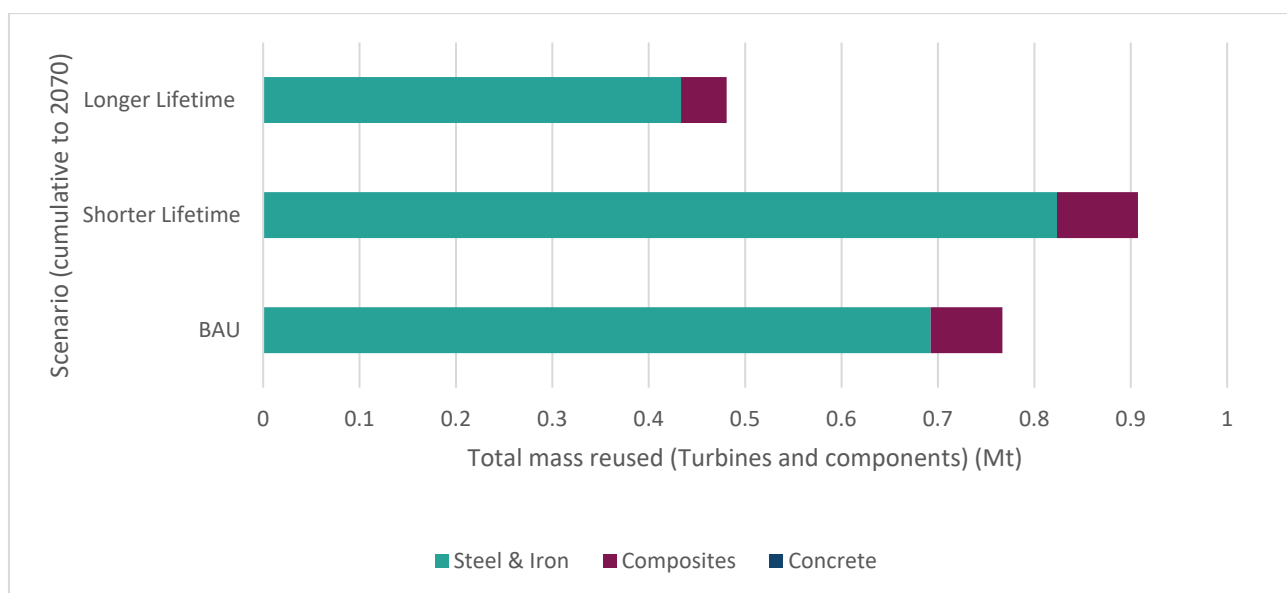


Figure 22: Onshore wind total reuse for each scenario and material (1990 to 2070).

Using the baseline reuse ratios outlined in Table 47, the shorter lifetime has the highest reuse potential, followed by BAU and then longer lifetime (Figure 22). Although a greater total volume of material is handled in the longer lifetime scenario, the higher baseline reuse ratios applied to earlier decommissioning result in greater overall reuse in the shorter lifetime case. However, this should be considered in the context of RQ1a, as the shorter lifetime scenario, by contrast, has the highest net material impact per energy generation.

Given the remaining research gaps and lack of empirical data on reuse practices, it is also important to consider sensitivities with different reuse fractions. Figure 23 shows the results from the reuse ratio sensitivity analysis.

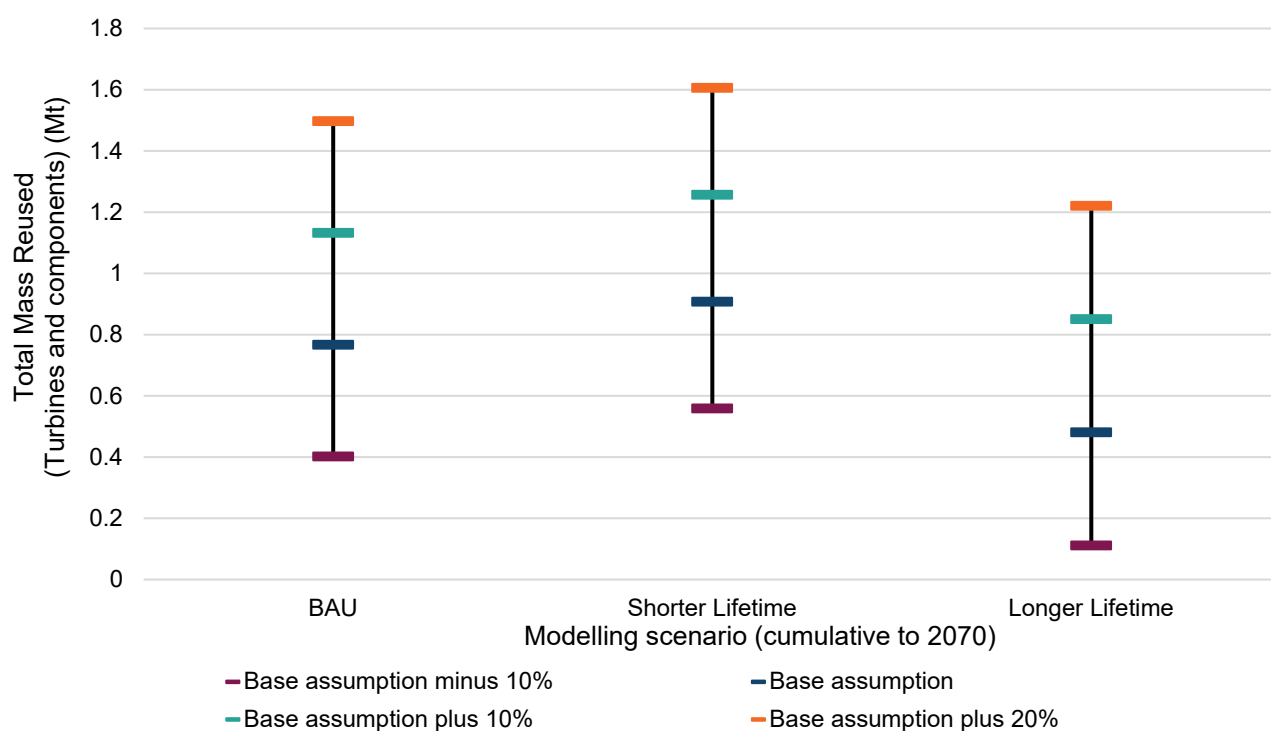


Figure 23: Onshore wind total reuse ratio sensitivity analysis for each scenario (1990 to 2070).

As the reuse ratios are varied for each scenario, by -10% up to +20%, the difference between the longer and shorter lifetime total reuse decreases by 13.9%. The sensitivity bars in Figure 23 show the significant variation in reused mass as the reuse ratios are altered. Up to 0.7 Mt of additional material are available for reuse as the reuse ratios increase by 20%.

Increasing component replacement rates between the minimum and maximum replacement scenarios (Table 20), the largest impact is on the longer lifetime scenario with an increase of 25.6% in total material reuse. Total material reuse increases by 24.3% for BAU, followed by 19.8% for shorter lifetime.

Figure 24 shows the results of the estimated reuse mass from the sensitivity analysis, in which the ratios of reuse, material recovery and non-recovery were kept constant across all scenarios.

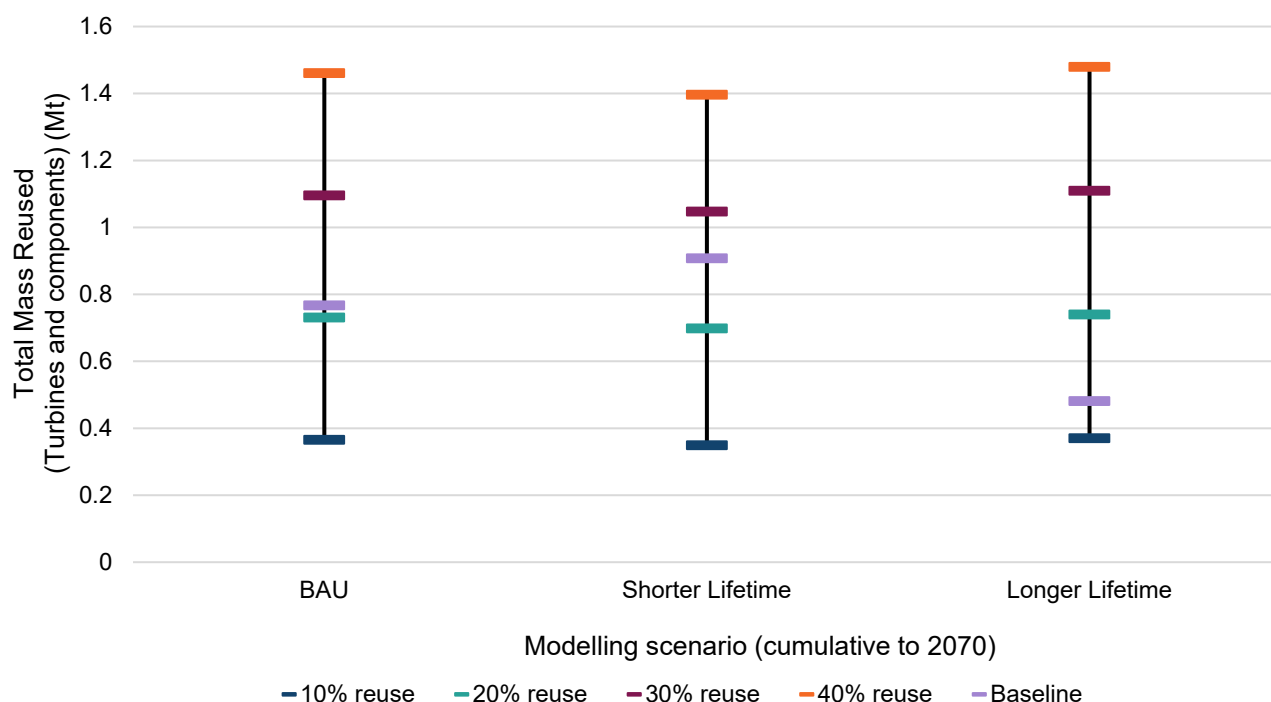


Figure 24: Onshore wind total reuse ratio sensitivity analysis for each scenario with constant handling ratios (1990 to 2070).

When keeping the handling ratios constant across the lifetime scenarios, shown for reuse ratios of 10-40%, it shows that the total reuse masses are quite similar across the scenarios, and that the variations of the lifetime scenarios in the baseline scenario are stemming from the definition of different reuse fraction, rather than significant differences of total masses. The results are ranging from ~0.4 Mt to ~1.4 Mt and consequently very sensitive to the definition of the reuse ratios in the material flow model.

This underpins the importance to conduct further analysis on the reuse potential, including the consideration of assessing remaining useful life, which is in contrast, also of importance for assessing the potential of lifetime extensions of the existing wind assets (RQ1b).

3.2.4.1.2 Material Recovery

Table 24 shows the material recovery mass for each scenario in onshore wind of each material in scope.

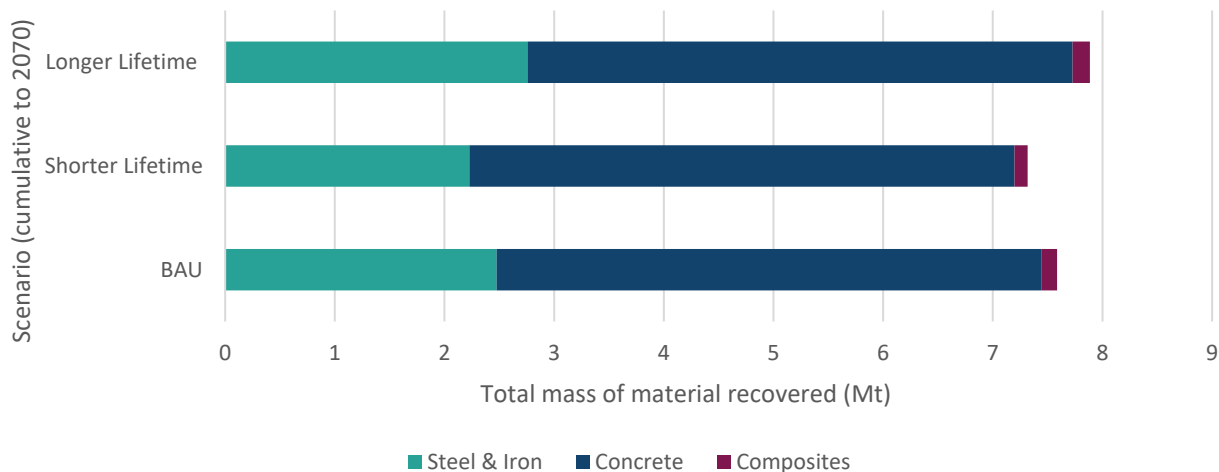


Figure 25: Onshore wind total material recovery for each scenario and material (1990 to 2070).

Using the baseline material handling values outlined in Table 14, the longer lifetime has the highest material recovery, followed by BAU and then shorter lifetime (Table 24). The amount of concrete recovered for each scenario is constant due to no concrete assumed to be reused for any scenario. The highest steel, iron and composites are recovered from the longer lifetime scenario, followed by BAU and shorter lifetime using the baseline handling ratios. Material recovery sensitivities are outlined in Appendix B.3 Material flow sensitivities, and key results outlined in the following.

For steel and iron, the base material recovery assumption was 95%. Figure 26 shows the results from the steel and iron recovery ratio sensitivity analysis.

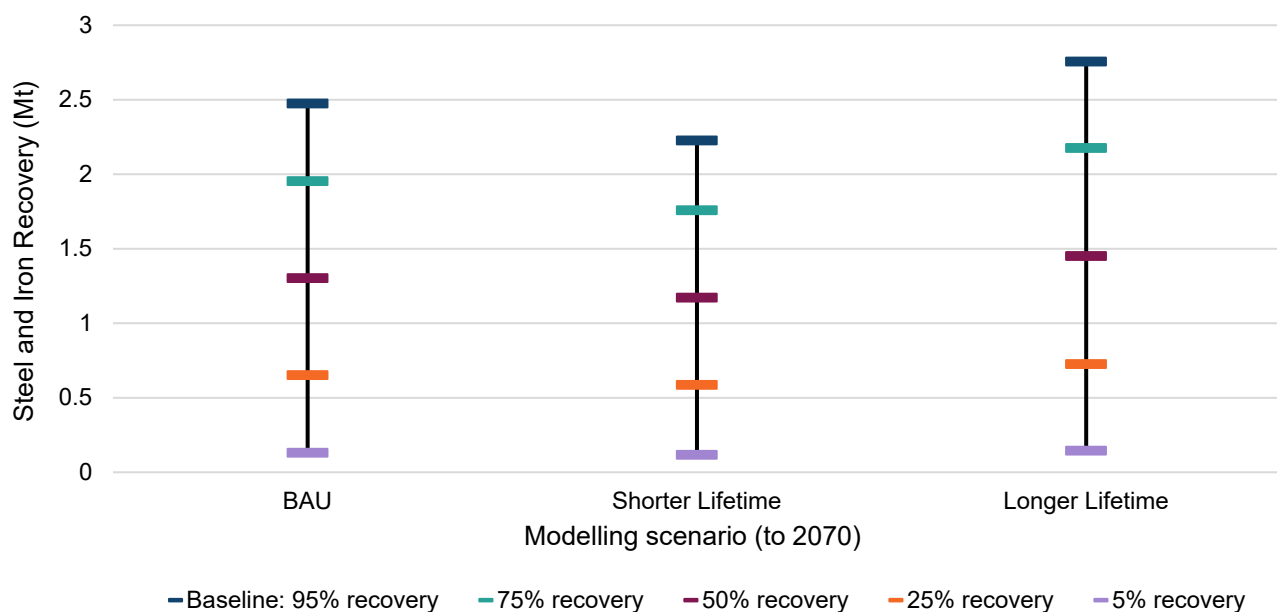


Figure 26: Onshore wind steel and iron recovery ratio sensitivity analysis for each scenario (1990 to 2070).

Up to 2.6 Mt of additional steel and iron is estimated to be recovered as recovery rates are increased from 5% to 95%. This sensitivity is of particular interest, given that achieving 95% material recovery is technically feasible, although it is currently mostly carried out outside of the UK.

For composites, the base material recovery assumption was 50%, hence assuming the establishment of blade recycling infrastructure in Europe. Figure 27 shows the results from the composite recovery ratio sensitivity analysis.

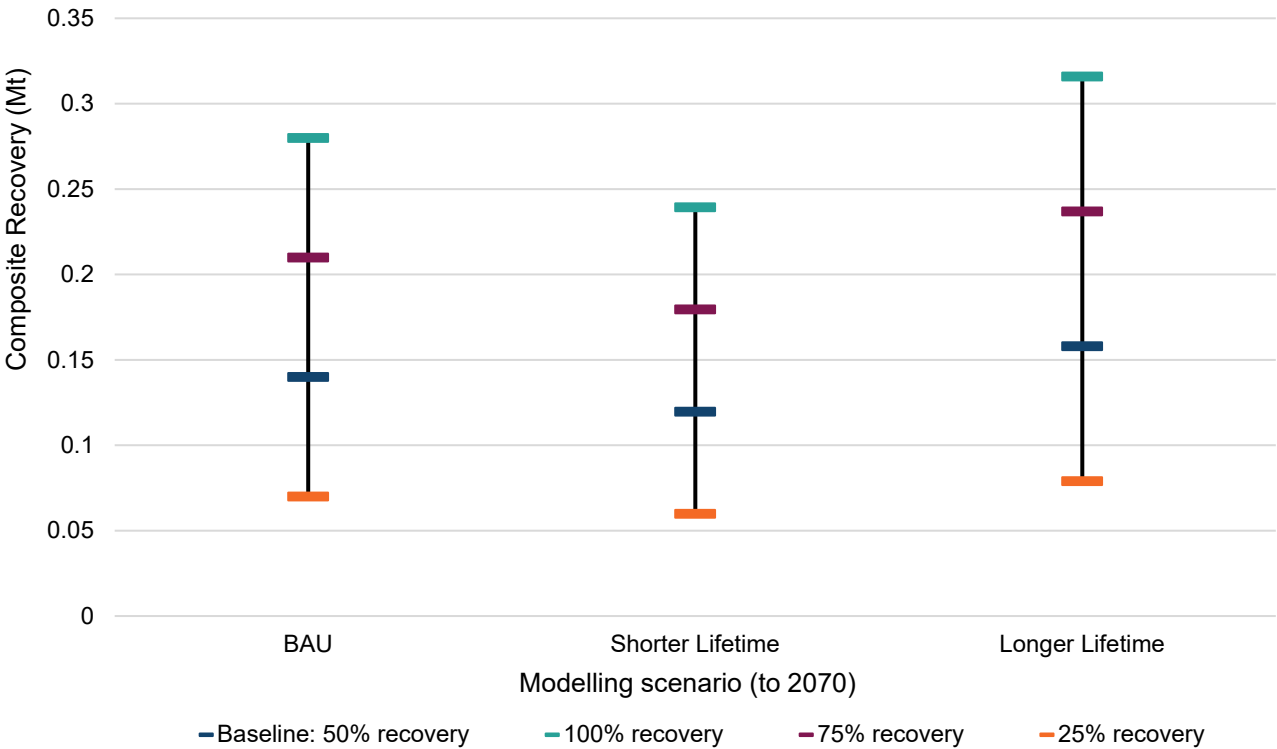


Figure 27: Onshore wind composite recovery ratio sensitivity analysis for each scenario (1990 to 2070).

For composites, approximately 0.2 Mt of additional material could be recovered as recovery rates are increased from 25% to 100%. For all scenarios, an additional 7.5 Mt of concrete was estimated to be recovered as recovery rates increased from 25% to 100%.

3.2.4.1.3 No material recovery

In case no recovery on turbine, component or material level takes place, the remaining mass is assumed to be not recovered. Hence possible options for handling would, for instance, be landfilling or incineration with energy recovery.

Figure 28 presents the results of the total material not recovered from onshore wind for each scenario and material in scope.

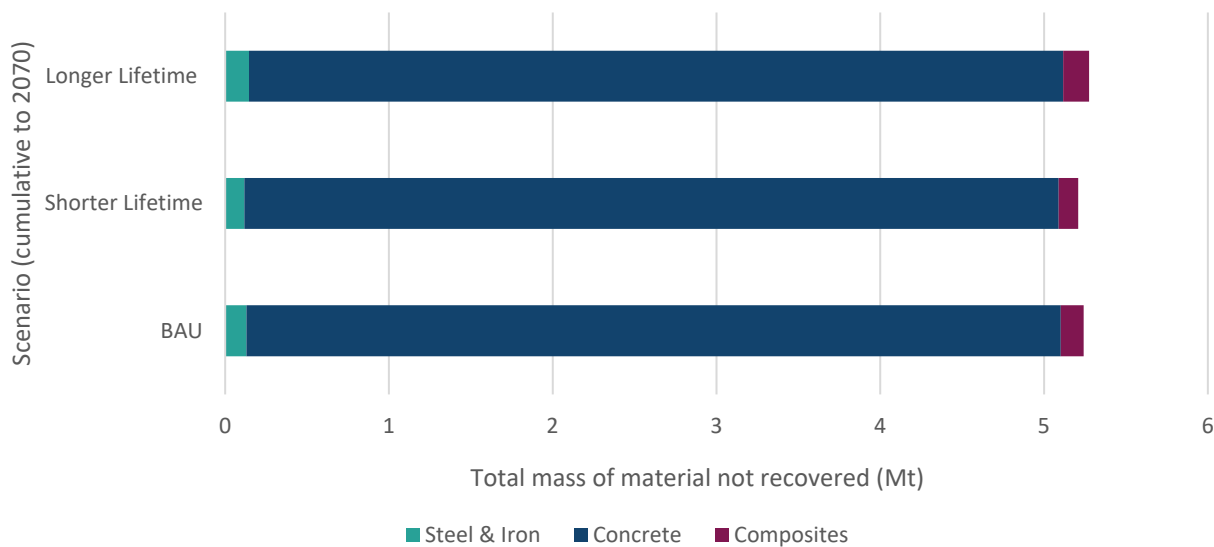


Figure 28: Onshore wind total material not recovered for each scenario and material (1990 to 2070).

In Figure 28, using the baseline material handling values, the longer lifetime also has the highest amount of no recovery, followed by BAU and then shorter lifetime. However, the total no-recovery masses of the scenarios are in a similar order of magnitude, ranging from 5.2-5.3 Mt. Given, the high recovery ratios for steel and iron, the mass is relatively small, while for concrete a significant amount is assumed not to be recovered.

3.2.4.2 Offshore wind

The total mass of material, including decommissioning of installed offshore wind turbines and replacement of components, produced from each scenario is shown in Table 29, assuming 100% removal of the foundation/substructure.

Table 29: Offshore wind total mass of material handled from each scenario from 2004 until 2050 and 2070.

Scenario	Total material mass (Mt)	
	2050	2070
BAU	5.6	11.9
Shorter	7.8	11.8
Longer	3.4	12.1

As in Section 3.2.2, significant material mass is excluded from the analysis when the timeline is restricted to 2050, especially for longer lifetime and BAU scenarios. Approximately 8.7 Mt and 6.4 Mt are excluded from the longer and BAU scenarios respectively, while only 4.0 Mt are

missed from the shorter lifetime. Due to the later installation date for offshore wind, there is significantly more material when extending the timeline from 2050 to 2070 in comparison to onshore wind.

Figure 29, Figure 30 and Figure 31 show the annual material handling mass values for each scenario, split into turbine and component reuse (second lifecycle), material recovery and no recovery. These figures further demonstrate the impact of timeline on the total material mass. The shorter lifetime is expected to be fully handled by 2052, while longer lifetime is still being handled up until approximately 2062.

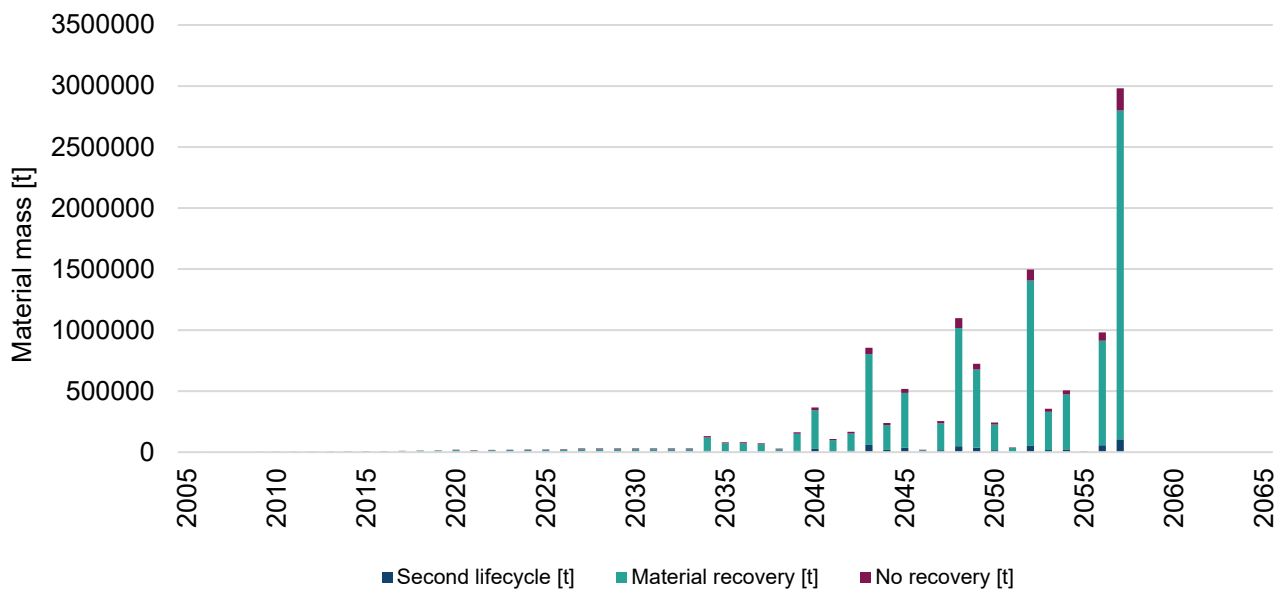


Figure 29: Offshore wind BAU lifetime scenario annual material handling following decommissioning and replacements of blades, generators and gearboxes during operation (2004 – 2065).

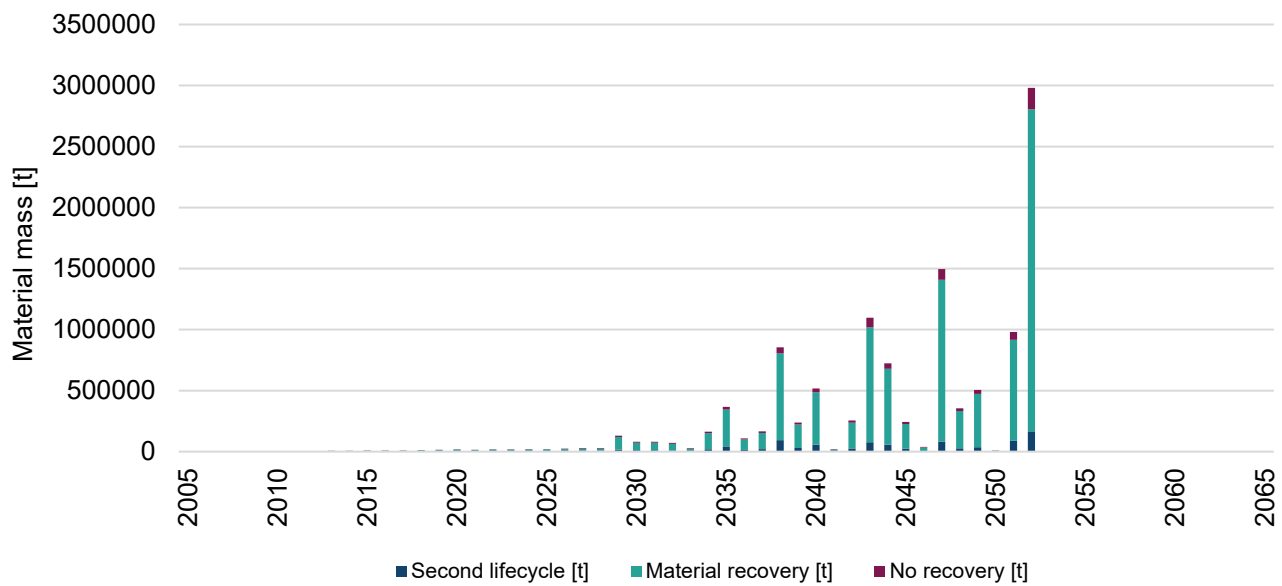


Figure 30: Offshore wind shorter lifetime scenario annual material handling following decommissioning and replacements of blades, generators and gearboxes during operation (2004 – 2065).

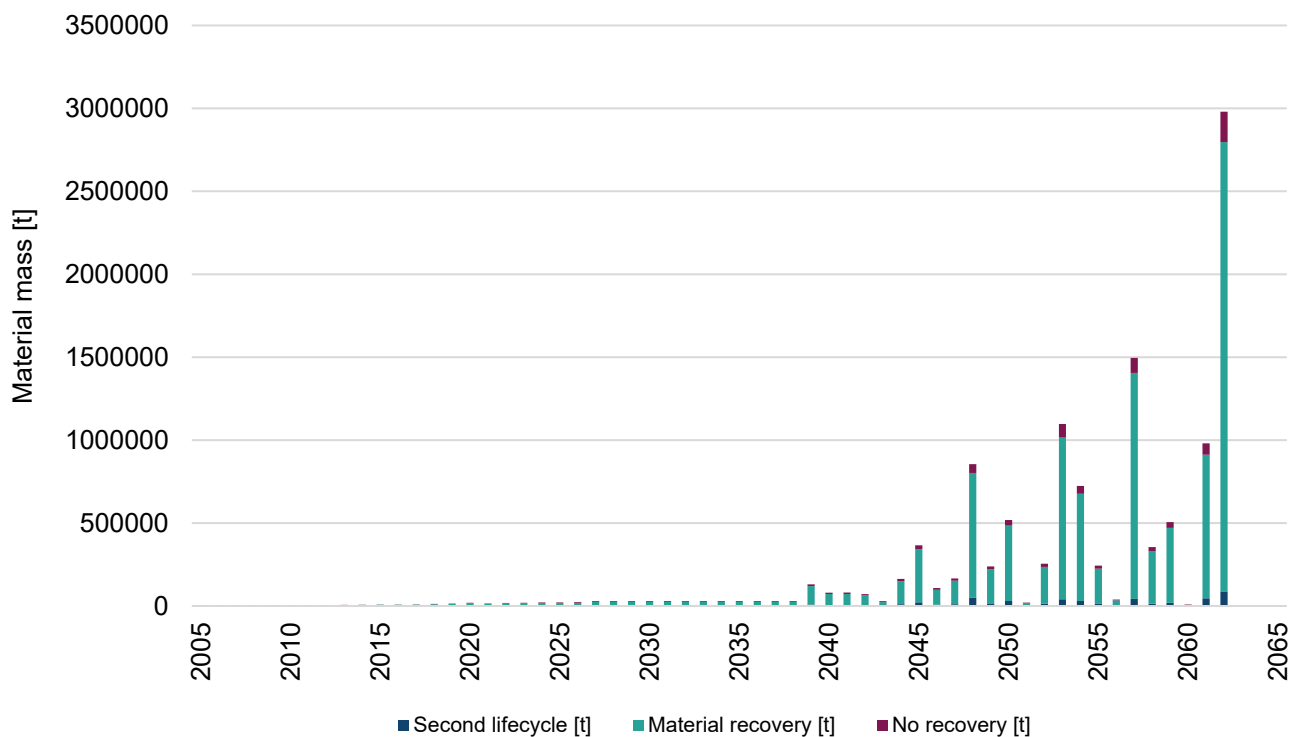


Figure 31: Offshore wind longer lifetime scenario annual material handling following decommissioning and replacements of blades, generators and gearboxes during operation (2004 – 2065).

The total handling mass from each scenario is a combination of the installed wind farm assets and the component replacements throughout the total lifetime. Figure 29, Figure 30 and Figure 31 show the differences in reuse, recovery and no recovery, respectively, for each scenario. Concrete has been excluded from these figures as the total handled mass is negligible (0.02

Mt for all scenarios) when compared with steel, iron and composites. The handling ratios are based on the values outlined in Section 3.1.2.2.2.

3.2.4.2.1 Reuse

Figure 32 outlines the total reuse of wind turbines and components for each scenario in offshore wind, expressed in steel & iron mass and composite mass.

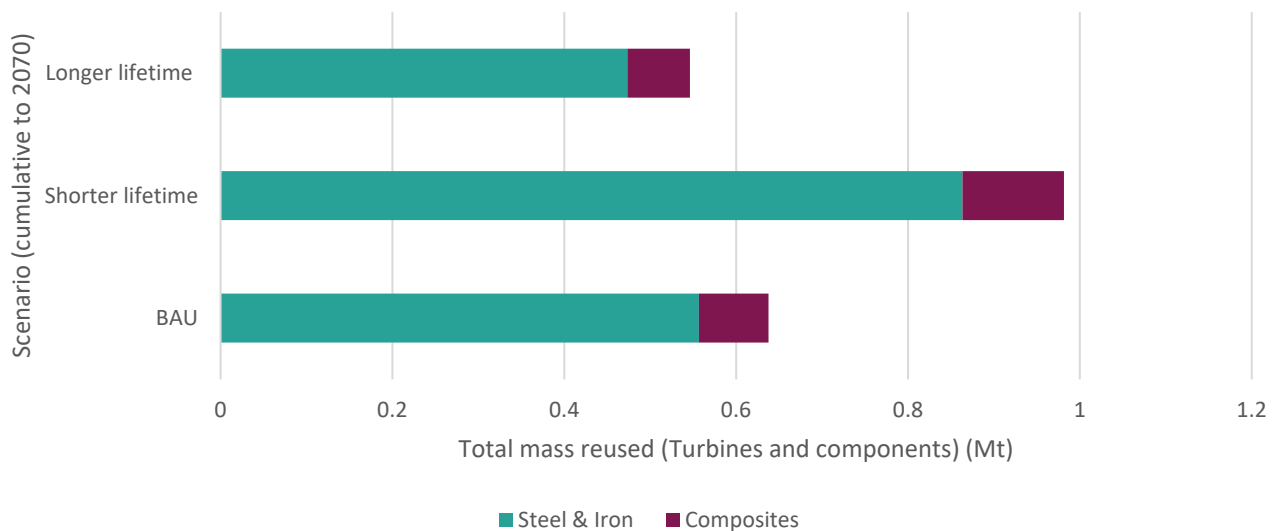


Figure 32: Offshore wind total reuse for each scenario and material (2004 to 2065).

Similarly to onshore wind, the shorter lifetime has the highest reuse potential, followed by BAU and then longer lifetime. Across the scenarios, a smaller reuse fraction is assumed when comparing to the onshore wind scenarios. Moreover, steel and iron from the foundation/substructure at time of decommissioning is not assumed to be reused. For offshore wind, the higher baseline reuse ratio applied to the shorter lifetime scenario, consequently, results in greater overall reuse potential, in contrast to the other two scenarios.

While reuse and refurbishment activities take place for component replacements, there is currently a lack of experience on the removal, decommissioning and handling of offshore wind turbine and their foundations/substructures. The lack of empirical data underpins the importance for a sensitivity analysis. Figure 33 shows the results from the reuse ratio sensitivity analysis.

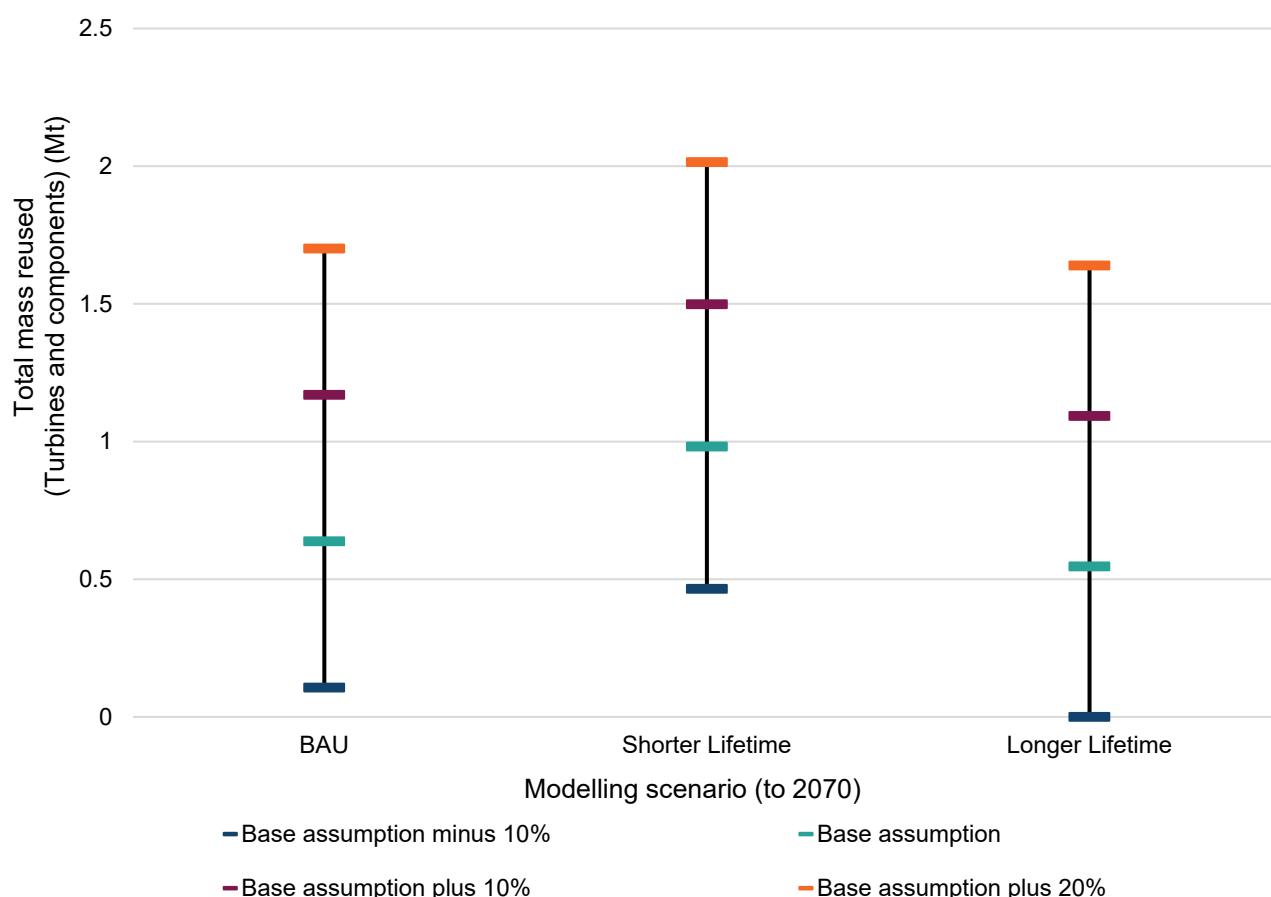


Figure 33: Offshore wind total reuse ratio sensitivity analysis for each scenario (2004 to 2065).

As the reuse ratios are varied for each scenario, by -10% up to +20%, the difference between the reuse potential of the longer and shorter lifetime scenario decreases by 19.2%. The sensitivity bars in Figure 33 show the significant variation in reused mass as the reuse ratios are altered. Up to 1.1 Mt of additional material are available for reuse as the reuse ratios increase by 20%.

When testing the impact on reuse of increasing component replacement rates between the minimum and maximum replacement scenarios, the largest impact is on the BAU with an increase of 41.9% in total material reuse. Total reuse increases by 37.8% for shorter lifetime, followed by 32.9% for longer lifetime.

The base assumption applies different reuse ratios across the scenarios. If the handling ratios are kept constant across the lifetime scenarios, the differences between the scenarios become even smaller than shown in Figure 33. Consequently, this highlights the importance of understanding and quantifying the link between asset decommissioning timing, remaining lifetime, and reuse potential in future studies.

3.2.4.2.2 Material recovery

Figure 34 shows the material recovery mass for each scenario in offshore wind of each material in scope.

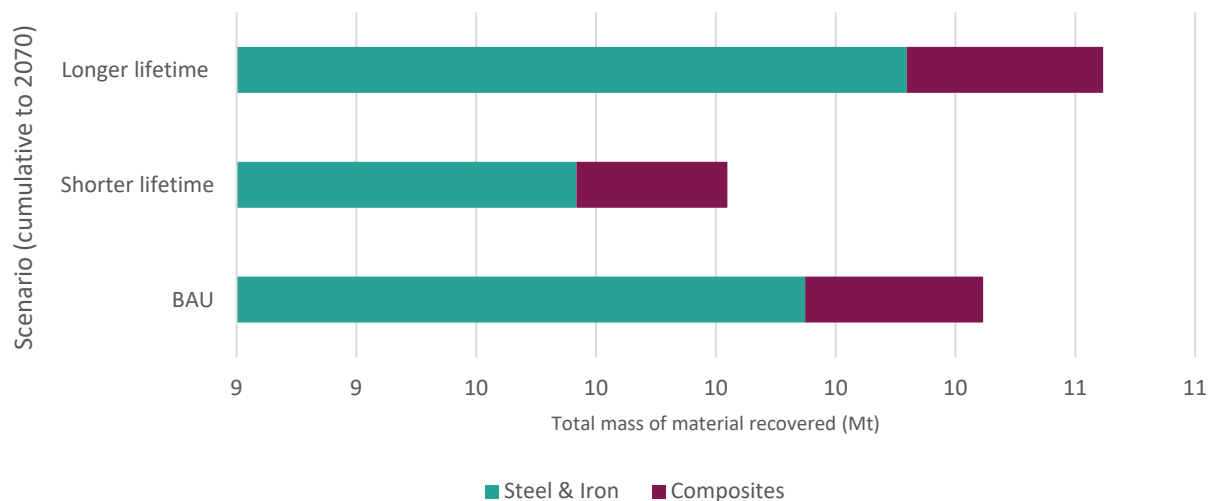


Figure 34: Offshore wind total material recovery for each scenario and material (2004 to 2065).

For offshore wind the longer lifetime has the highest material recovery, followed by BAU and then shorter lifetime (Figure 34), when using the baseline handling values outlined in Table 47. This is further put into context by the material recovery sensitivities, that are outlined in Appendix B.3 Material flow sensitivities and key results outlined in the following.

For steel and iron, the base material recovery assumption was 95%. Figure 35 shows the results from the steel and iron recovery ratio sensitivity analysis.

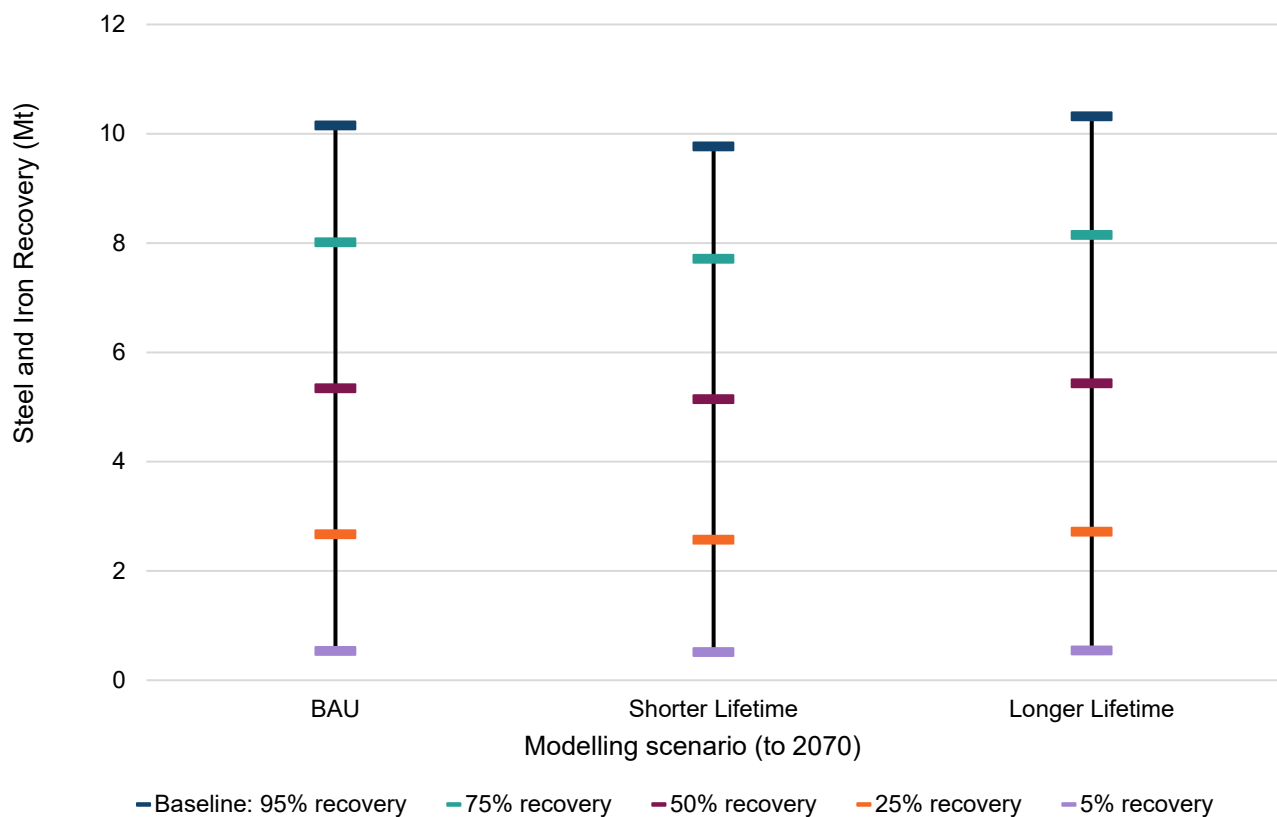


Figure 35: Offshore wind steel and iron recovery ratio sensitivity analysis for each scenario (2004 to 2065).

Up to 9.8 Mt of additional steel and iron is estimated to be recovered as recovery rates are increased from 5% to 95%.

Figure 36 shows the results from the composite recovery ratio sensitivity analysis, allowing to understand variations from the base material recovery assumption of 50%.

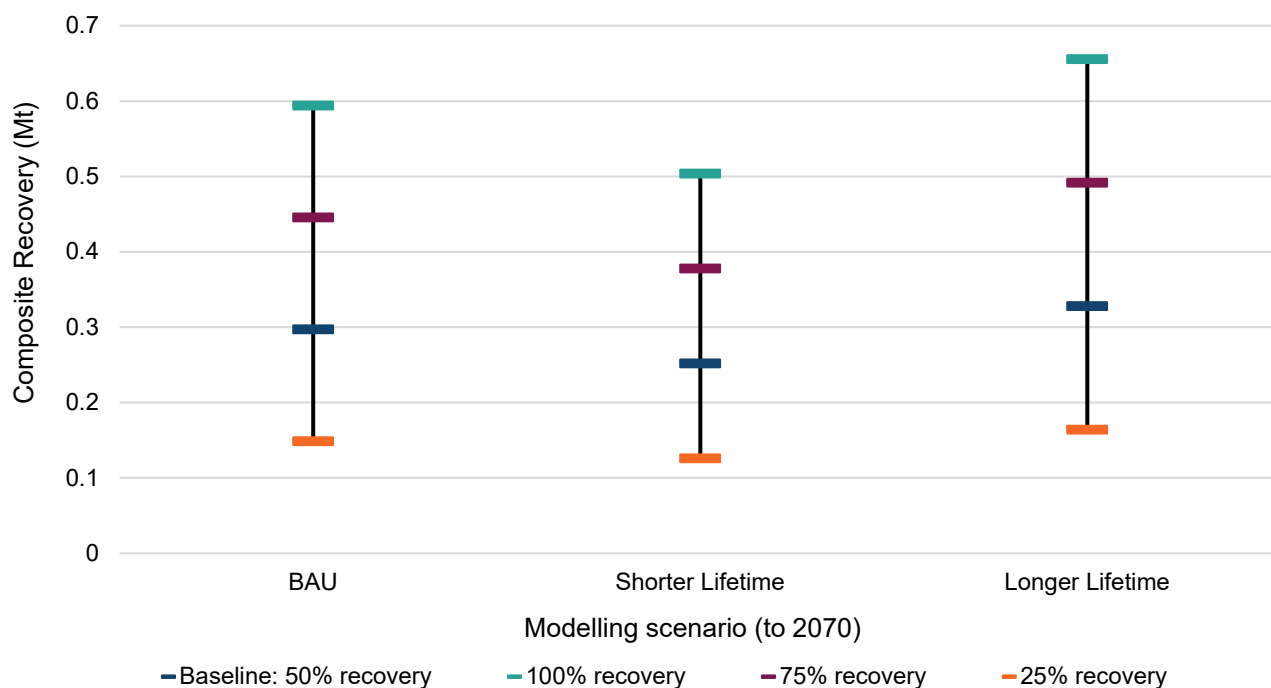


Figure 36: Offshore wind composite recovery ratio sensitivity analysis for each scenario (2004 to 2065).

For composites, approximately 0.5 Mt of additional material could be recovered as recovery rates are increased from 25% to 100%.

3.2.4.2.3 No material recovery

Figure 37 presents the results of the total material not recovered from offshore wind for each scenario and material in scope, ranging from 0.7-0.9 Mt across the scenarios.

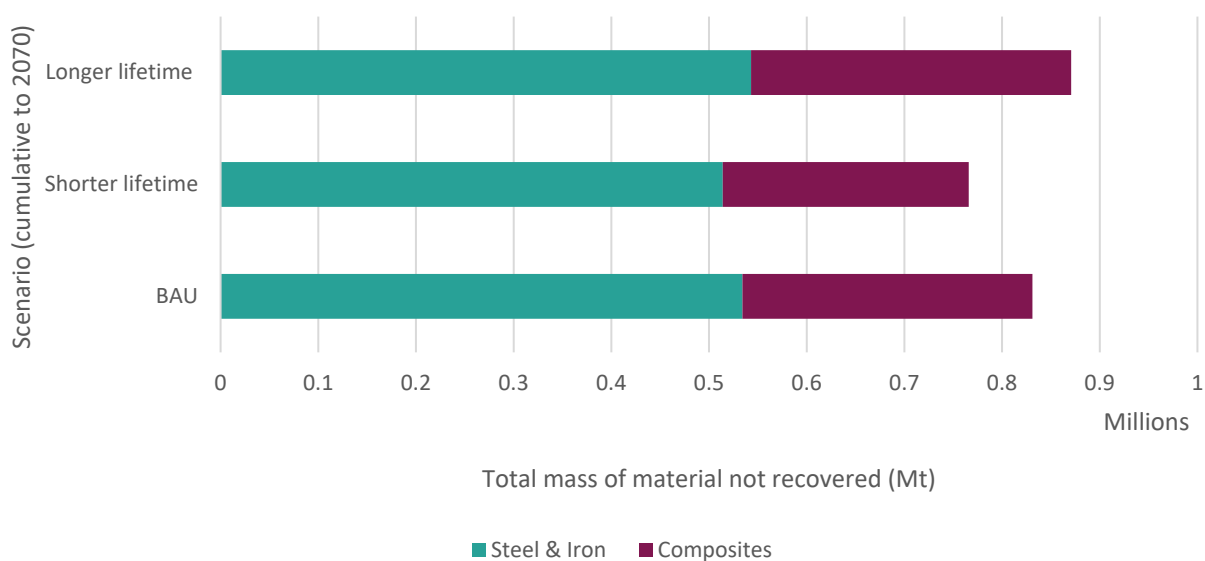


Figure 37: Offshore wind total material not recovered for each scenario and material (2004 to 2065).

Using the baseline material handling values outlined in Table 47, the longer lifetime also has the highest amount of no recovery, followed by BAU and then shorter lifetime (Figure 37).

3.2.4.2.4 Summary of potential for reuse and recovery

Summarising the findings for onshore and offshore wind in this section.

For onshore wind, the following was observed:

- For the BAU scenario, the estimated reuse is 0.8 Mt, while recovery and no recovery is 7.6 Mt and 5.2 Mt, respectively.
- For the shorter lifetime scenario, the estimated reuse is 0.9 Mt, while recovery and no recovery is 7.3 Mt and 5.2 Mt, respectively.
- For the longer lifetime scenario, the estimated reuse is 0.5 Mt, while recovery and no recovery is 7.9 Mt and 5.3 Mt, respectively.

The shorter lifetime scenario results in the highest reuse mass (0.9 Mt), due to a larger quantity of earlier decommissioned wind turbines that are assumed to have an increased reuse potential. Reuse in the BAU scenario is only marginally lower at 0.8 Mt, whilst the longer lifetime scenario shows the lowest reuse mass (0.5 Mt). Assuming constant recovery ratios across scenarios, the longer lifetime scenario produces the highest recovered material mass (7.9 Mt) due to the increased overall handling material in this scenario. This is followed by the BAU scenario (7.6 Mt), while the shorter lifetime scenario yields the lowest recovered mass (7.3 Mt).

For offshore wind, the following was observed:

- For the BAU scenario, the estimated reuse is 0.6 Mt, while recovery and no recovery is 10.5 Mt and 0.8 Mt, respectively.
- For the shorter lifetime scenario, the estimated reuse is 1.0 Mt, while recovery and no recovery is 10.0 Mt and 0.8 Mt, respectively.
- For the longer lifetime scenario, the estimated reuse is 0.5 Mt, while recovery and no recovery is 10.7 Mt and 0.9 Mt, respectively.

Similarly to onshore wind, the shorter lifetime scenario results in the highest reuse mass (1.0 Mt), due to the earlier decommissioned of wind turbines increasing reuse potential. Reuse under the BAU scenario is lower at 0.6 Mt, while the longer lifetime scenario again produces the lowest reuse mass (0.5 Mt). Assuming constant recovery ratios across scenarios, the longer lifetime scenario yields the highest recovered material mass (10.7 Mt), followed by the BAU scenario (10.5 Mt) and the shorter lifetime scenario (10.0 Mt).

Considering the aggregate of estimated flows from both onshore and offshore wind, the total handling mass being reused and recovered was estimated to up to 14.7 Mt of steel and iron. Onshore wind accounted for 23% to this, while 77% stems from offshore. A significant mass of steel and iron from offshore is found in the foundation and substructures, meaning recovery depends on whether these structures are removed from the site rather than left in situ. From

the handled composites (approximately 0.6 Mt), 34% and 66% came from onshore and offshore wind, respectively. In contrast, the majority of concrete (up to 5 Mt) stems from onshore wind, contributing 99.7%.

Regarding reuse potential, up 1.7 Mt of steel and iron could be reused through whole turbine reuse and component reuse (e.g. generators and gearboxes), from both onshore (49% contribution) and offshore wind (51% contribution). Composite reuse from blades was estimated up to 0.2 Mt, with 42% stemming from onshore and 58% from offshore.

For material recovery, up to 13.0 Mt of steel and iron was estimated, 79% from onshore and 21% from offshore wind. Composite recovery was estimated up to 0.5 Mt, with 33% stemming from onshore and 67% from offshore. All concrete handling mass is from material recovery, so remains up to 5.0 Mt with 99.7% from onshore wind.

Given the variations in annual estimates from component replacements and decommissioning across the different scenarios, it is recommended to also consider the trends over time and not only the totals, when formulating policy and industry measures.

3.2.5 RQ3a: What are the potential economic impacts of the repair and recovery activities?

This section outlines the aggregate impacts in terms of both job creation and GVA, providing a high-level summary of the total economic contributions associated with the analysis. A more detailed breakdown of employment and GVA generation, disaggregated by individual parameters and assumptions, is presented in section 3.2.6.

3.2.5.1 Onshore wind

The total values presented for the onshore analysis incorporate the following key parameters associated with the turbine lifecycle:

- Major component exchange, including blades, gearboxes, and generators
- Decommissioning activities at end-of-life
- Turbine and component refurbishment
- Material recovery of concrete, steel and iron, and composite materials

It should be noted that the GVA impacts associated with turbine downtime have not been included within the analysis.

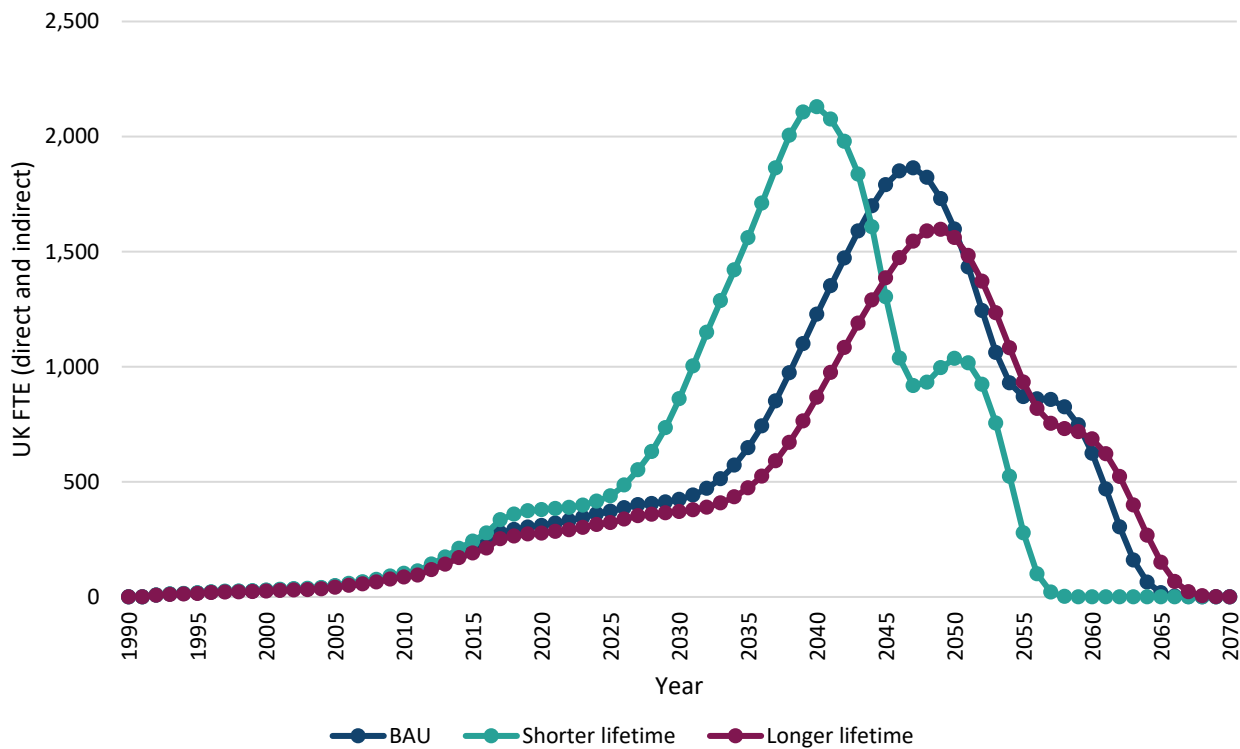


Figure 38: Total annual UK FTE (direct and indirect) associated with onshore repair and recovery activities

Figure 38 illustrates the annual distribution of jobs through to 2070 across the different scenarios. Figure 39 presents the corresponding GVA profile, which follows a broadly similar trajectory reflecting that both metrics are driven by the same underlying lifecycle activities.

The shorter lifetime scenario exhibits a more pronounced and earlier peak in both employment and GVA, reflecting the accelerated pace of decommissioning and associated activities as assets reach end-of-life more quickly. This results in a sharper concentration of labour demand within a relatively narrow time window.

In contrast, the BAU and longer lifetime scenarios show a more gradual build-up in employment, with jobs and GVA distributed more evenly over time. Extending asset lifetimes delays the need for large-scale decommissioning, allowing refurbishment and continued operation to play a greater role in sustaining capacity. As a result, economic impacts are spread over a longer period, reducing short-term pressure on supply chains and workforce capacity.

The peak in the short lifetime scenario occurs between 2035 and 2040, whereas in the longer lifetime scenario it is delayed to between 2045 and 2050. This shift highlights how asset lifetime decisions can influence and smooth economic requirements, providing more time for workforce development, skills planning, and industrial scaling.

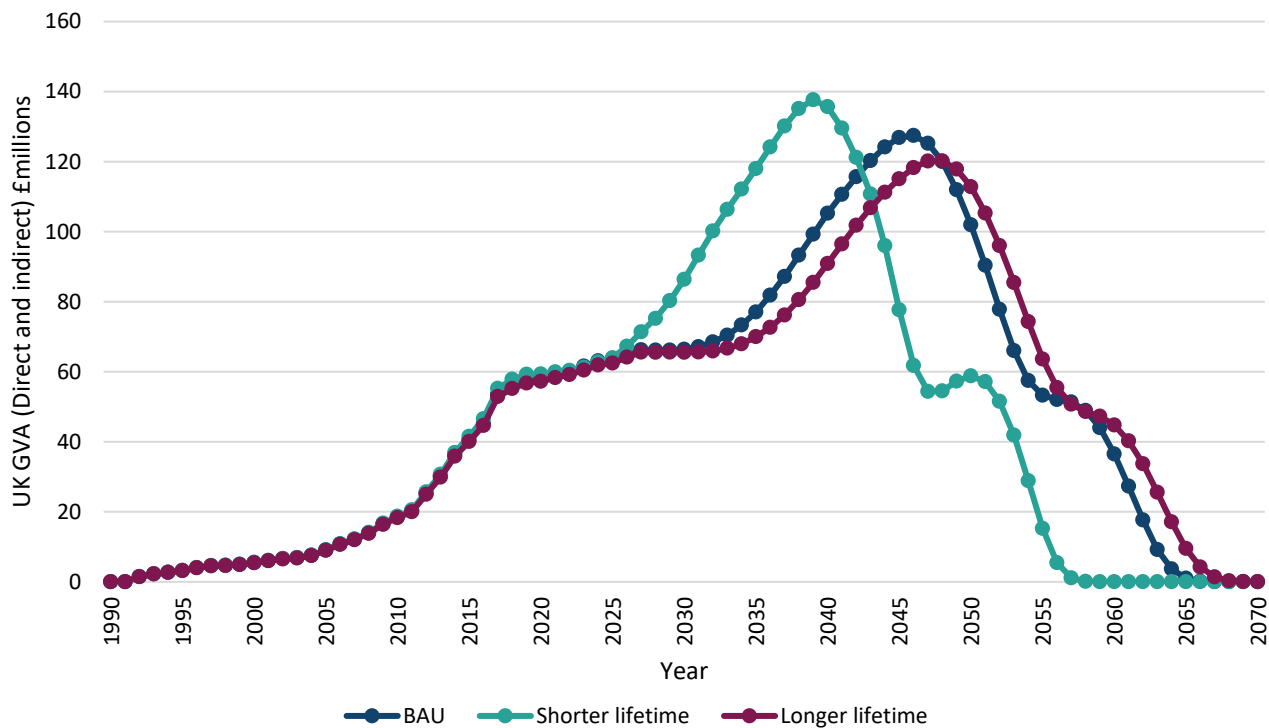


Figure 39: Total annual UK GVA (direct and indirect) £millions associated with onshore repair and recovery activities

Table 30 presents the total cumulative economic impacts associated with onshore wind repair and recovery activities, with Figure 40 and Figure 41 showing the breakdown of employment and GVA by activity. It can be seen that for employment, refurbishment is the metric with the greatest variation between scenarios, driven by higher reuse assumptions, whilst for GVA, MCE is the major variable parameter.

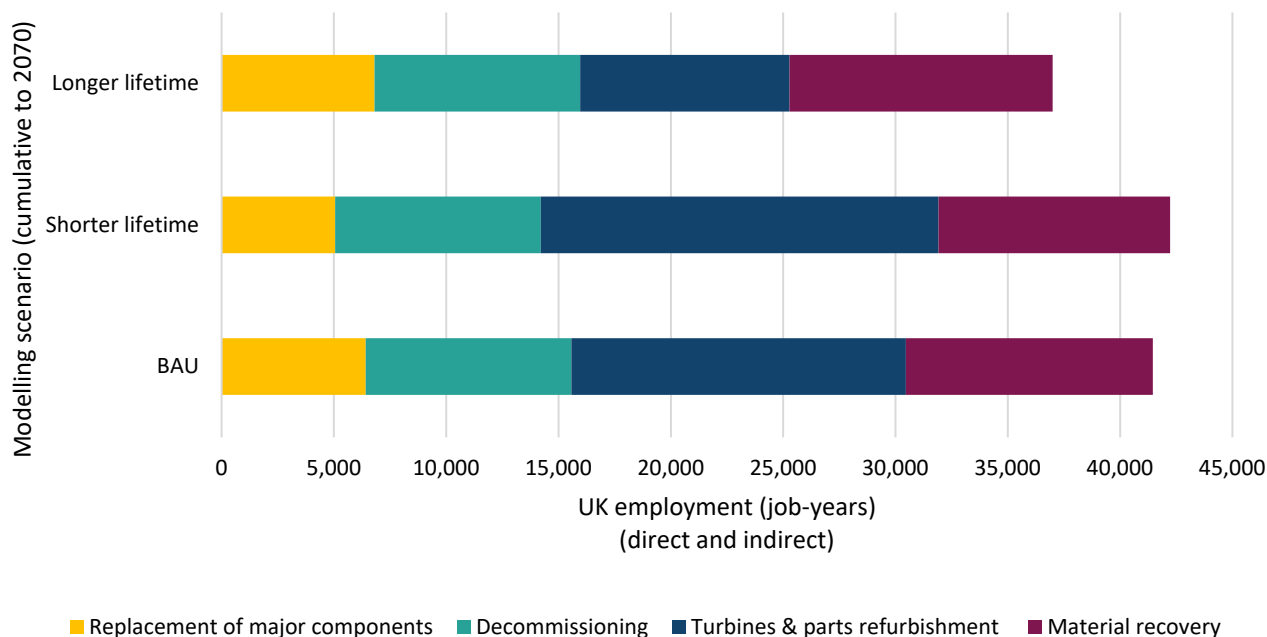


Figure 40: Total UK employment (job-hours) (direct and indirect) for onshore repair and recovery broken down by activity

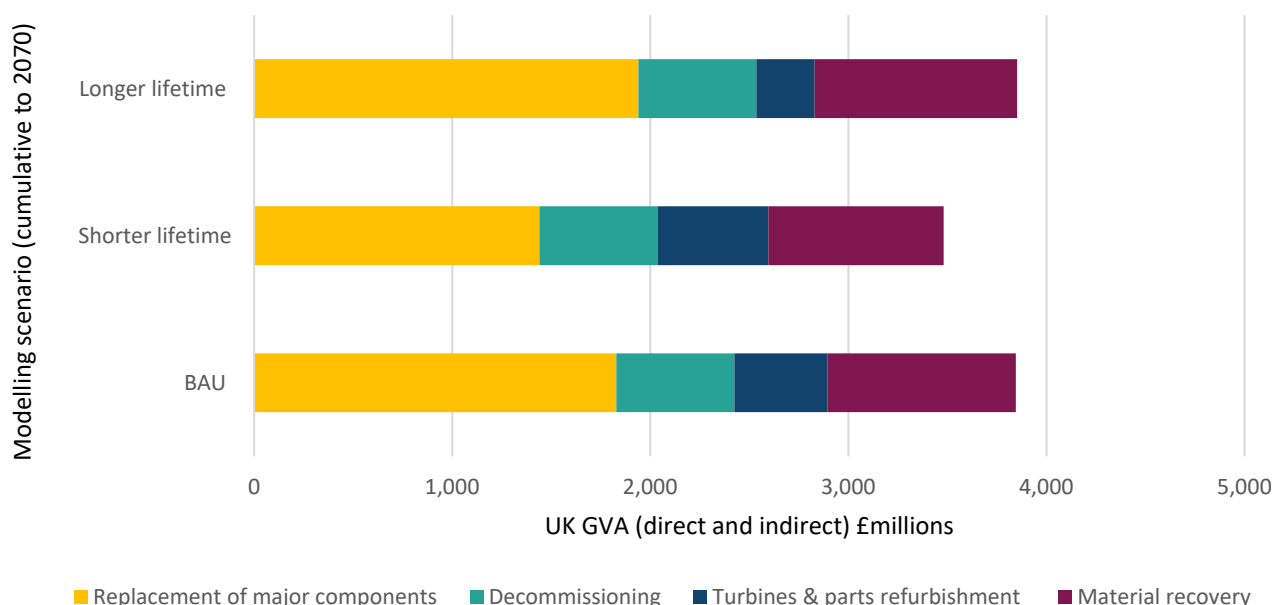


Figure 41: Total UK GVA (£million) (direct and indirect) for onshore repair and recovery broken down by activity

When employment is considered in isolation, the shorter lifetime scenario delivers the highest employment impact, followed closely by the BAU and longer lifetime scenarios, although the differences between them remain relatively modest with 5,000 jobs between the highest and lowest scenarios. However, for GVA the opposite pattern is observed, with the shorter lifetime scenario generating the least economic impact overall. In this case, the major component exchange (MCE) phase acts as the principal driver of value creation, with its contribution becoming even more significant once broader O&M impacts are included. While repair and

recovery activities alone suggest a slight employment advantage for the shorter lifetime case, the inclusion of full lifecycle impacts changes the picture considerably. When broader O&M effects are taken into account, the longer lifetime scenario emerges as the most economically beneficial overall, reflecting the sustained employment, operational activity, and value creation associated with extended asset operation.

Table 30: Total UK economic impacts (direct and indirect) associated with onshore repair and recovery activities (with and without O&M) (cumulative to 2070)

Scenario	Repair and recovery		Including O&M ⁵	
	Employment (Job-years)	GVA (£million)	Employment (Job-years)	GVA (£million)
BAU	41,000	3,850	481,000	13,150
Shorter	42,000	3,500	389,000	10,800
Longer	37,000	3,850	504,000	13,700

This highlights the importance of taking a whole-system, lifecycle perspective when assessing economic outcomes. Focusing on a narrow subset of activities can lead to different conclusions than those reached when O&M and longer-term operational benefits are included, underscoring the need for comprehensive analysis in informing investment and policy decisions. It should also be noted that the economic impacts associated with turbine and component reinstallation, as well as repowering, are outside the scope of this study. These activities may nevertheless generate significant additional economic impacts that are not captured within the current assessment.

3.2.5.2 Offshore wind

The total values presented in the offshore analysis incorporate the following key parameters associated with the turbine lifecycle:

- Decommissioning activities at end-of-life (UK GVA assumed to be 18% (Outer Dowsing Offshore Wind, 2025), reflecting the use of predominantly non-UK jack-up vessels and offshore support infrastructure)
- Turbine and component refurbishment
- Material recovery of steel and iron and composite materials

UK employment and GVA associated with major component exchange, including blades, gearboxes, and generators is assumed to be 0% due to reliance on international specialist

⁵ Total aggregated O&M estimates used in place of MCE estimates to avoid double counting

vessels and supply chains⁶, this is likely to be an underestimate however insufficient data was available to accurately model this parameter. These assumptions are important in defining the proportion of activity that translates into domestic economic impact for offshore wind where a significant share of high-value offshore operations is delivered through international supply chains.

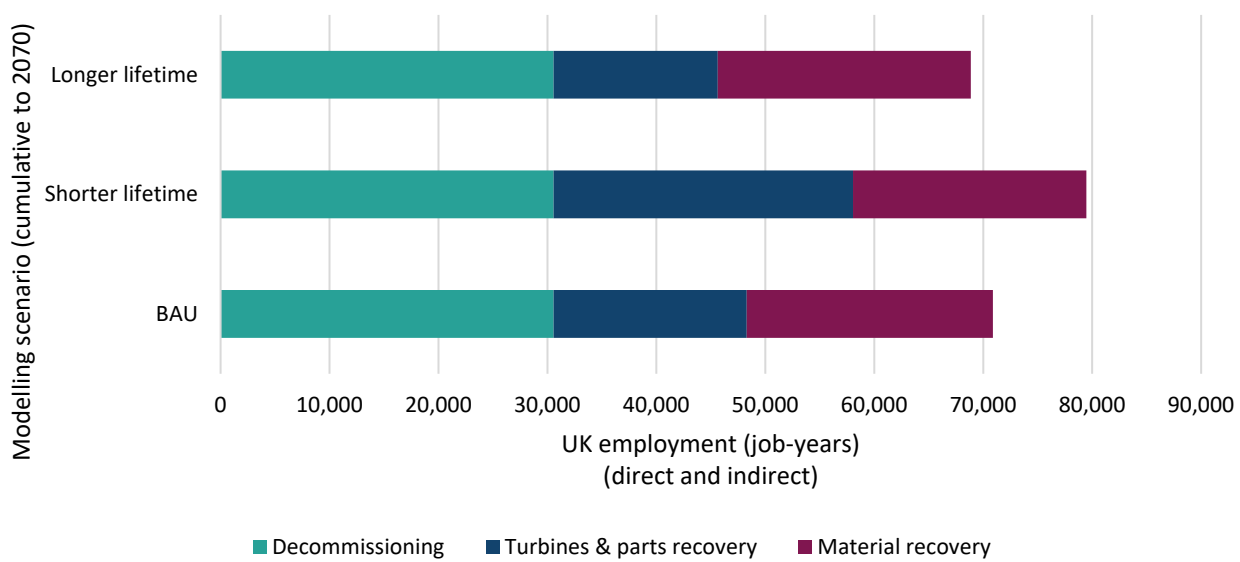


Figure 42: Total UK employment (job-hours) (direct and indirect) for offshore repair and recovery broken down by activity

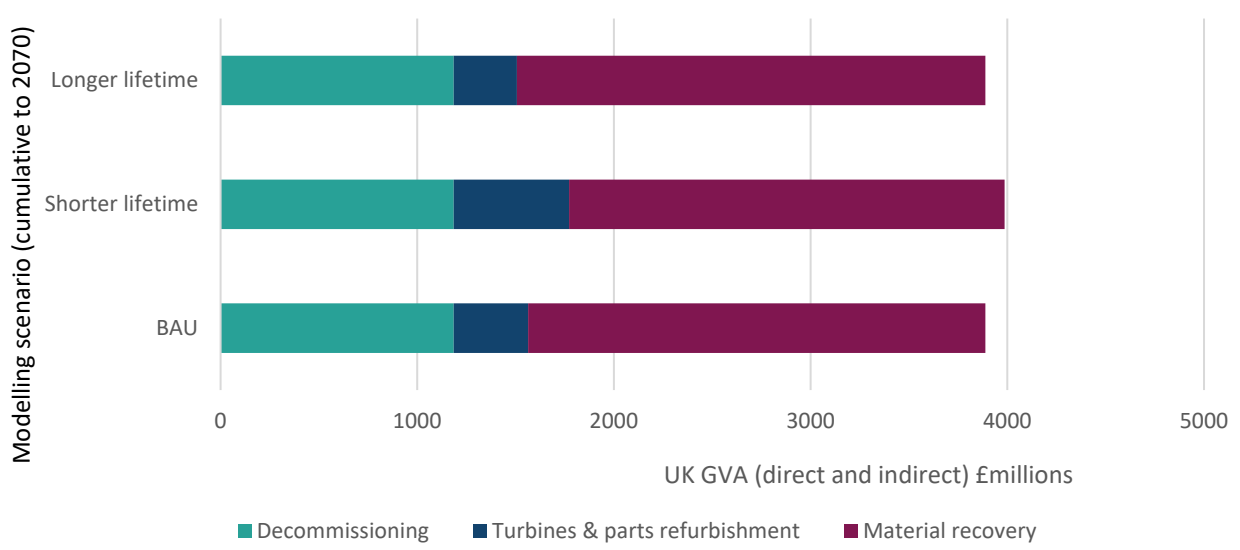


Figure 43: Total UK GVA (£million) (direct and indirect) for offshore repair and recovery broken down by activity

Figure 42 and Figure 43 shows that when considering repair and recovery activities in isolation, the shorter lifetime scenario delivers the highest level of employment and GVA. In this case, the difference between the shorter and longer lifetime scenarios is approximately

⁶ Further information can be found in section 3.2.6.1.2

10,500 job-years, indicating a relatively clear advantage for the shorter lifetime case within this limited scope of activities, driven by turbine and part refurbishment. The variation in GVA across scenarios is more limited.

However, looking at Table 31 this pattern changes once O&M impacts are included. When the full lifecycle is considered, the longer lifetime scenario becomes the most economically beneficial overall. This reflects the sustained employment associated with continued asset operation, which outweighs the increased activity associated with shorter lifetimes.

Table 31: Total UK economic impacts (direct and indirect) associated with offshore repair and recovery activities (with and without O&M) (cumulative to 2070)

Scenario	Repair and recovery		Including O&M	
	Employment (Job-years)	GVA (£million)	Employment (Job-years)	GVA (£million)
BAU	71,000	3,900	1,150,000	16,900
Shorter	79,500	4,000	981,000	14,800
Longer	69,000	3,900	1,330,000	19,100

This shift in results highlights the importance of considering the full range of lifecycle activities when assessing economic impacts. While repair and recovery phases are more concentrated under shorter lifetimes, O&M activity accumulates over time and becomes increasingly significant in shaping total employment outcomes. As a result, lifecycle duration has a material influence on both the scale and distribution of economic benefits.

It is also important to note that the relatively low assumed UK content in key offshore activities, particularly MCE and decommissioning, represents a missed opportunity for domestic economic capture. A substantial proportion of high value offshore work is instead delivered through international vessels and supply chains. This limits the extent to which these lifecycle phases translate into UK employment and GVA, despite their significance in the overall offshore wind value chain.

3.2.6 RQ3b&c: What are the respective potential job and GVA impacts for repairing and recovering material from existing wind assets?

The jobs and GVA associated with repair and recovery activities are presented in this section, with results disaggregated by individual activity types across the value chain. This breakdown enables a more granular assessment of the economic impacts associated with different stages of repair, refurbishment, reuse, and material recovery, reflecting the varying labour intensity and value creation of each activity. For each activity the total jobs and GVA has been

calculated, including both direct and indirect impacts. The methodology for how this has been calculated can be found in Appendix C.1 Economic modelling methodology.

3.2.6.1 Major component exchange

The estimate of MCE is limited to blades, generators, and gearboxes. These components were selected as they represent the most frequently replaced high-value items in turbine lifecycles and are consistently reported in the available literature. Other components, such as the nose cone, transformer, main shaft, and yaw ring, have been excluded due to limited data availability and less consistent reporting. This introduces a degree of conservatism into the analysis, as the associated jobs and GVA impacts are likely to be underestimated.

3.2.6.1.1 Onshore

The economic impacts for MCE in onshore wind turbines are based on a Bonus 1.3 MW turbine, which has been used as a proxy due to the availability of detailed cost and labour data at this scale. While this provides a consistent analytical baseline, it is not fully representative of the current onshore fleet. It is assumed that the number of jobs required for component replacement does not vary significantly with turbine capacity, as many activities (e.g. planning, mobilisation, and core installation tasks) are broadly similar across turbine sizes. However, costs are expected to scale with turbine capacity due to differences in component size, lifting requirements, and crane specifications. These factors can materially affect the cost structure of replacement activities and, by extension, the associated GVA estimates. As such, the results should be interpreted as indicative and subject to uncertainty associated with turbine model variability.

3.2.6.1.1.1 Jobs

Figure 44 shows the modelling results for the total job-years associated with onshore MCE based on the assumptions outlined in Appendix C: Economic impact assessment. The results indicate a positive relationship between asset lifetime and MCE related employment, with longer lifetime scenarios associated with a greater number of major component replacements and, consequently, higher job creation.

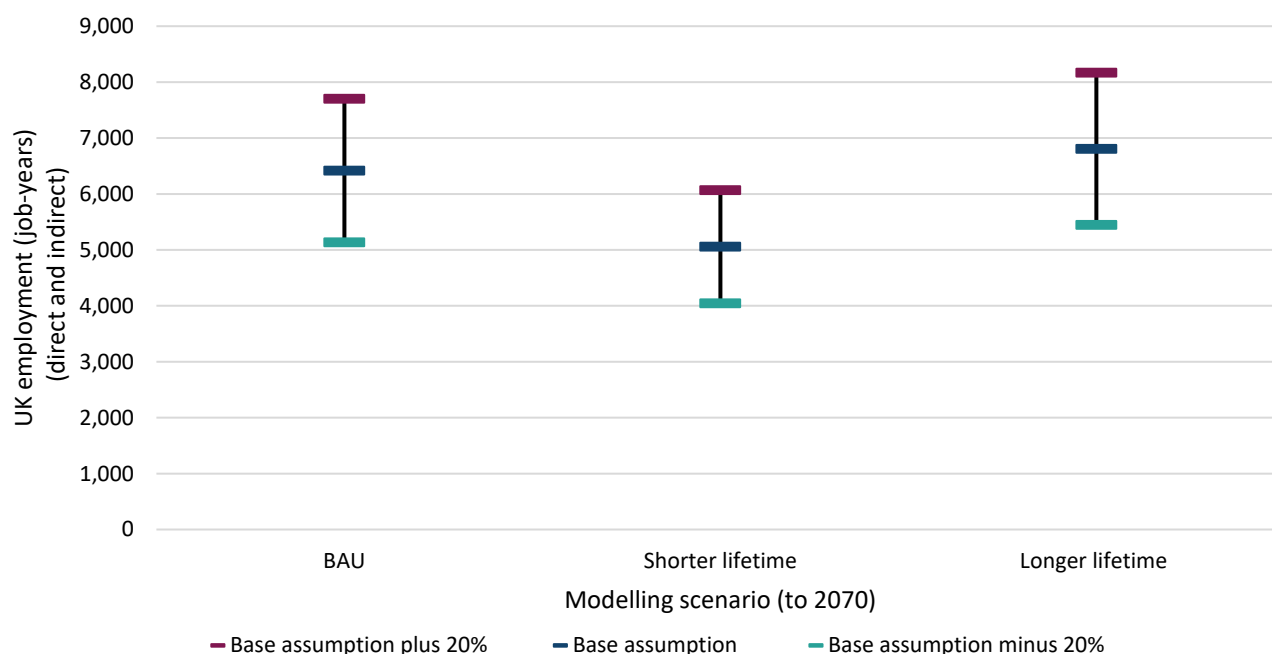


Figure 44: UK employment (job-years) (direct and indirect) associated with onshore MCE activities for each scenario including +/- 20% sensitivity on economic assumptions (cumulative to 2070)

To account for the uncertainty in scaling assumptions from the Bonus 1.3 MW turbine to the wider fleet, a sensitivity range of +/- 20% has been applied. While this introduces some overlap between scenario results, the overall pattern remains consistent, with the relative ordering of scenarios unchanged. This indicates that the main differences between scenarios remain stable despite the uncertainty in the scaling assumptions.

3.2.6.1.1.2 GVA

Figure 45 shows the modelling results for the total GVA associated with onshore MCE based on the assumptions outlined in Appendix C.2 [Economic modelling assumptions](#). As with jobs, the results indicate a positive relationship between asset lifetime and MCE related GVA, with longer lifetime scenarios associated with a greater number of major component replacements and, consequently, higher GVA creation.

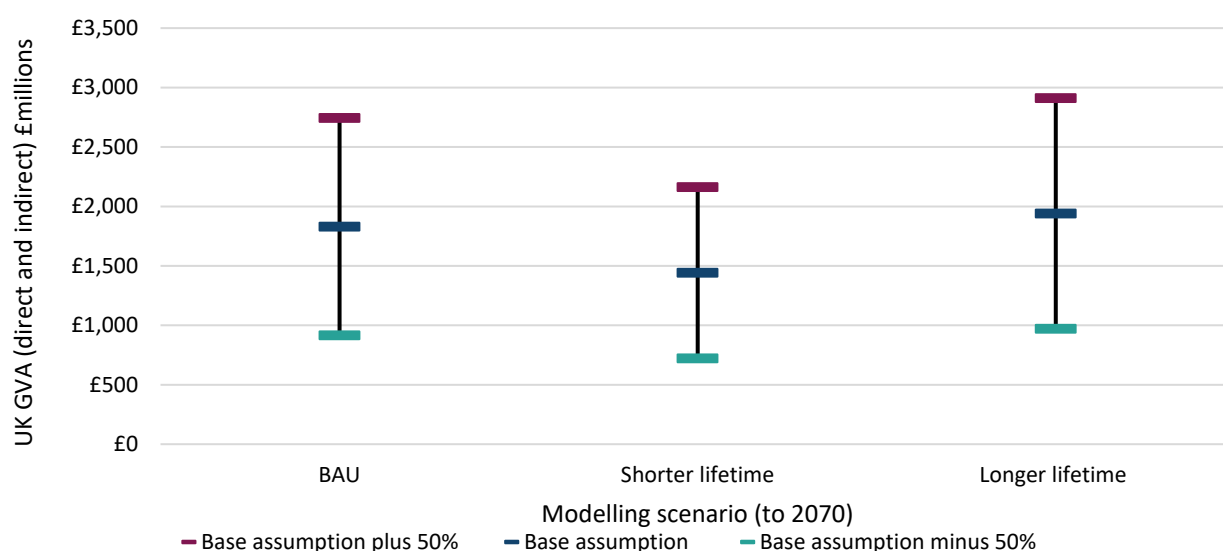


Figure 45: UK GVA £million (direct and indirect) associated with onshore MCE activities for all scenarios including +/- 50% sensitivity on economic assumptions (cumulative to 2070)

The GVA scaling assumptions from the 1.3 MW Bonus turbine have a higher degree of uncertainty associated with them, as the increase in GVA for larger onshore turbines may be quite substantial, particularly where larger cranes or more specialised equipment are required. To account for this increased uncertainty a sensitivity range of +/- 50% has been applied. This results in a reasonable level of overlap between the scenarios, indicating this increased uncertainty, and a significant range within scenarios. Nevertheless, the overall pattern remains consistent, with the relative ordering of scenarios unchanged. This indicates that the main differences between scenarios remain stable despite the uncertainty in the scaling assumptions.

3.2.6.1.2 Offshore

Offshore MCE activities are assumed to take place largely outside the UK economy, reflecting the structure of the existing supply chain and the specialised nature of the assets and services required. In particular, critical infrastructure, such as jack-up vessels, are predominantly owned and operated by non-UK companies, with limited domestic availability. In addition, many major components are manufactured overseas, meaning that a substantial share of the capital expenditure associated with replacement is captured outside the UK economy. As a result, much of the expenditure associated with component fabrication, vessel charter, heavy-lift operations, and associated logistics is captured outside the UK economy. While there may be some limited domestic inputs (e.g. port services, minor support activities), these are considered marginal in the context of overall MCE costs. Consequently, the jobs and GVA attributable to MCE has been conservatively estimated as zero within the UK, reflecting the high degree of supply chain leakage to international providers. The research review did identify UK based companies that are contracted by OEM's to carry out MCE activities, however there was insufficient evidence gathered to enable robust jobs and GVA estimates. It is recommended that further work is carried out to refine and improve the estimates associated with offshore MCE.

3.2.6.2 Decommissioning

The jobs and GVA associated with turbine decommissioning are assumed to be consistent across all lifetime scenarios, on the basis that all turbines will ultimately require decommissioning at the end of their operational life and that this will be captured by 2070 for all scenarios. As such, total decommissioning activity, and the associated economic impacts, are held constant across scenarios. The primary point of variation is therefore the timing of these impacts, with shorter lifetime scenarios bringing forward decommissioning activity, while longer lifetime scenarios defer it. This shift may have implications for the distribution of jobs and GVA over time, as well as for supply chain readiness and workforce planning, but does not materially affect the overall scale of decommissioning-related economic activity.

3.2.6.2.1 Onshore

3.2.6.2.1.1 Jobs

Decommissioning totals are assumed to be consistent across all scenarios (BAU, shorter lifetime, and longer lifetime), as the current fleet will be fully depleted by 2070. Table 32 shows the estimated number of jobs associated with decommissioning activities. Due to the uncertainty associated with the base assumptions, a +/- 20% sensitivity has been included to show the impact that changes may have on the final estimates.

Table 32: UK employment (job-years) (direct and indirect) associated with onshore decommissioning activities including +/- 20% sensitivity on the economic assumptions (cumulative to 2070)

Decommissioning employment (job-years) (direct and indirect)		
Base assumption	Base assumption +20%	Base assumption -20%
9,200	11,000	7,300

Whilst the total employment associated with decommissioning is unlikely to vary significantly between scenarios, the timing for requiring these roles is highly variable, as illustrated in Figure 46. This distinction is important for workforce planning, supply chain readiness, and regional economic impacts. In the shorter lifetime scenario, decommissioning activity is brought forward, creating a sharper and more concentrated labour demand, estimated to peak between 2035 and 2040. Requiring near term supply chain scale up and readiness. In contrast, whilst a similar trend is observed for the BAU and longer lifetime scenarios, decommissioning is deferred by approximately a decade, resulting in a more gradual ramp-up of activity and labour requirements.

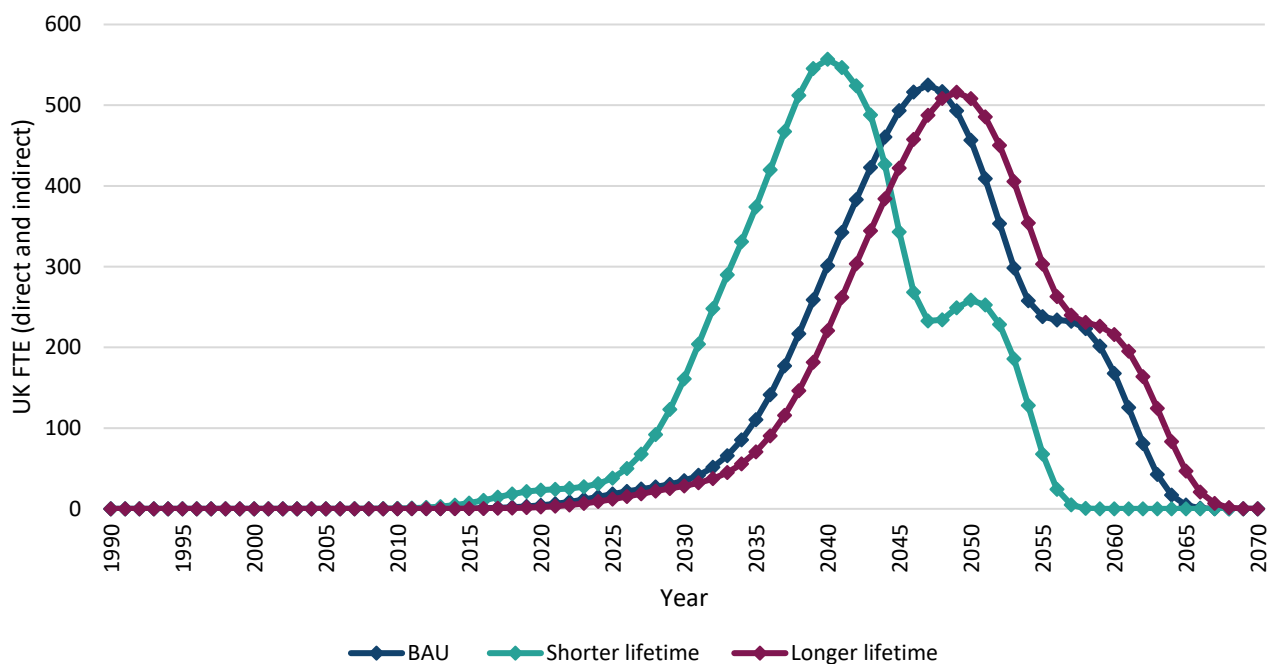


Figure 46: Annual onshore decommissioning jobs (direct and indirect) (1990-2070) for each scenario

3.2.6.2.1.2 GVA

As with jobs, the GVA associated with decommissioning activities is assumed to be fully recognised by 2070 for all scenarios (BAU, shorter lifetime, and longer lifetime). Table 33 shows the estimated GVA associated with UK onshore decommissioning. Due to the increased underlying uncertainty within the GVA assumptions, a slightly larger range of +/- 50% has been included.

Table 33: UK GVA (direct and indirect) £million associated with onshore decommissioning activities including +/- 50% sensitivity on the economic assumptions (cumulative to 2070)

Decommissioning GVA (direct and indirect) (£million)		
Base assumption	Base assumption +50%	Base assumption -50%
600	900	300

As shown in Figure 47, the trend for the timing of the GVA being recognised mirrors that of the jobs, with the shorter lifetime scenario resulting in an earlier and steeper peak, whilst BAU and the longer lifetime scenario are more similarly aligned. The differences between the scenarios are not substantial in terms of peak magnitude; rather, they are characterised by a somewhat faster ramp-up and tapering in the shorter lifetime case, compared to a more gradual build and decline under BAU and extended lifetimes.

This reflects the way in which asset lifetimes shape the sequencing of investment and associated economic activity. These profile differences are consistent with stakeholder feedback, which suggests that decommissioning project timelines are increasingly being pushed back. This indicates that the key consideration is not the overall level of GVA generated, but how it is distributed over time. A more gradual trajectory may better align with current market conditions and delivery constraints, supporting smoother capacity building and reducing the risk of bottlenecks, while a more front-loaded profile would require earlier and more coordinated interventions to ensure readiness across the supply chain.

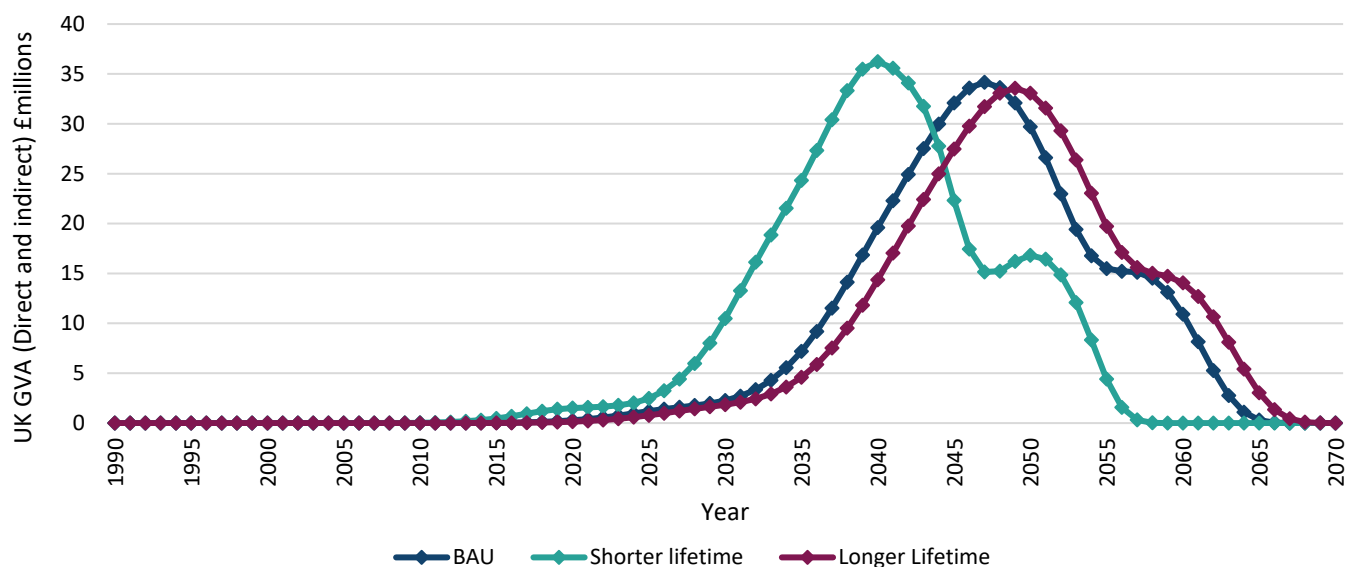


Figure 47: Annual onshore decommissioning UK GVA (direct and indirect) £million (1990-2070) for each scenario

3.2.6.2.2 Offshore

Given the limited number of offshore wind projects that have undergone full decommissioning, the available empirical evidence on associated costs and operational requirements remains sparse. Consequently, estimates for decommissioning a windfarm of this scale are necessarily derived from forward-looking models that draw on assumptions, industry benchmarks, and comparisons with analogous sectors, rather than extensive observed data. This reliance on projected inputs introduces inherent uncertainty into the modelling outputs, meaning that actual decommissioning costs and logistical complexities may diverge from those anticipated. In addition, assumptions regarding the distribution of economic activity, such as the proportion of the decommissioning contract expected to be secured domestically contribute to uncertainty, as these shares are sensitive to market conditions, supply chain capacity, and procurement strategies at the time of decommissioning.

3.2.6.2.2.1 Jobs

As with the onshore case, the offshore fleet is assumed to be fully decommissioned by 2070 in all scenarios. As a result, the cumulative scale of activity, and therefore the overall level of employment generated over the study period, is consistent across scenarios. Differences instead arise from the economic assumptions underpinning how decommissioning activity is delivered. However, offshore decommissioning remains subject to considerable uncertainty,

and large variations are reported across the literature. Table 34 illustrates the sensitivity of cumulative employment estimates to these underlying assumptions

Table 34: UK employment (job-years) (direct and indirect) associated with offshore decommissioning for a range of literature assumptions (cumulative to 2070)

Decommissioning employment (job-years) (direct and indirect)		
Chosen assumption (713 FTE per GW)	Higher literature estimate (927 FTE per GW)	Lower literature estimate (307 FTE per GW)
30,600	39,700	13,200

The variation therefore largely reflects uncertainty surrounding the offshore decommissioning process itself. This includes differences in assumed removal methods, vessel operations, and project sequencing. Variations in the complexity of offshore sites and future technological developments also contribute to the wide range of employment estimates reported in the literature.

3.2.6.2.2.2 GVA

The costs associated with offshore decommissioning is subject to even greater variability than the employment impacts, with values in literature varying by up to a factor of 10. The chosen value is closer to the lower end of the estimates, this has been selected as it is based on figures used by industry opposed to more academic studies. Table 35 shows the impact of this variability on the modelled GVA, where a similarly wide range of outcomes is observed.

Table 35: UK GVA (direct and indirect) £million associated with offshore decommissioning for a range of literature assumptions (to 2070)

Decommissioning GVA (direct and indirect) £million		
Chosen assumption (£44,667 per MW)	Higher estimate (£480,000 per MW)	Lower estimate (£42,667 per MW)
1,200	12,700	1,100

For the chosen GVA assumption, 18% of the GVA is attributed to the UK based on Outer Dowsing Offshore Wind, 2025. The relatively modest domestic share reflects structural characteristics of the offshore wind supply chain, including the concentration of specialised heavy-lift vessels and decommissioning expertise, as well as the globalised nature of procurement practices. While some activities are likely to be UK-based, higher-value or highly

specialised tasks may be sourced from established overseas contractors, limiting the domestic capture of expenditure. Figure 48 shows the impact on GVA of varying this assumption to capture a higher proportion of offshore decommissioning activities within the UK.

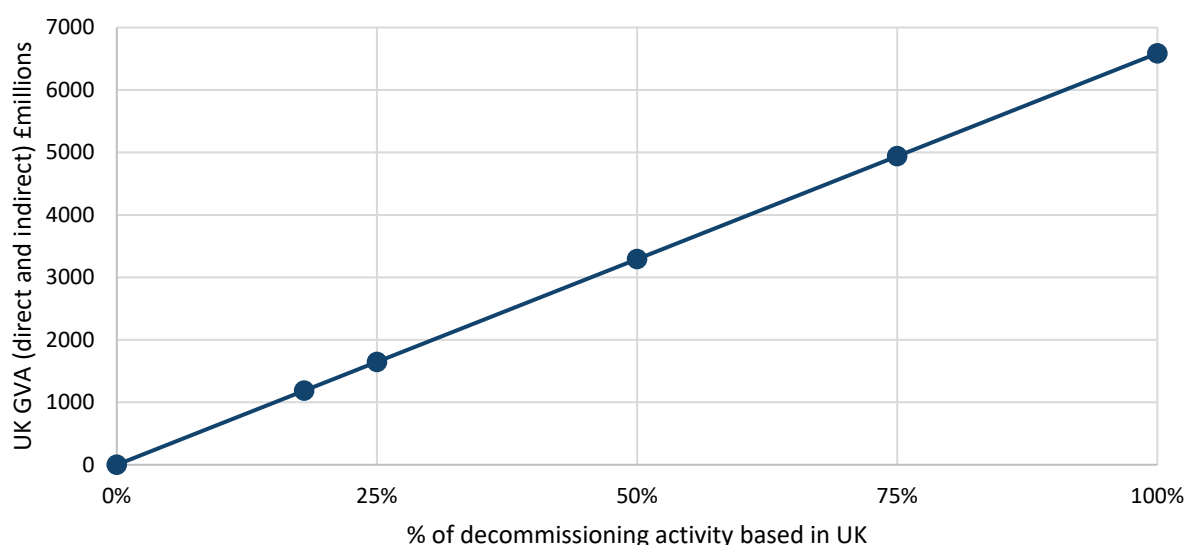


Figure 48: UK GVA (direct and indirect) £millions sensitivity to % of offshore decommissioning activities carried out in the UK (cumulative to 2070)

This indicates a significant potential opportunity for the UK supply chain that is currently not being fully realised, particularly in areas such as specialised vessel provision and high-value engineering services. Increasing domestic capability and participation in these segments could materially enhance the proportion of value captured within the UK economy.

3.2.6.3 Refurbishment

It is assumed that a proportion of the turbines and components recovered for reuse undergo refurbishment prior to redeployment, with the remainder prepared for direct reuse across all scenarios. This reflects the expectation that several major elements, most notably towers and blades, which together account for a significant proportion of total turbine mass, are more likely to be suitable for reuse with limited intervention rather than full refurbishment. As a result, a 10% refurbishment rate of total reuse mass is assumed as the base case and is intended to approximate the relatively small share of components requiring more labour-intensive processing. The associated economic intensities are derived from BVG Associates, 2023.

These assumptions introduce uncertainty into the modelling. The refurbishment rate itself may vary depending on technical condition, regulatory requirements, and market dynamics. In particular, the modelling does not explicitly account for demand-side constraints or uncertainties in end markets for reused components, which may significantly influence the feasible scale of reuse in practice. This distinction has important implications for employment estimates, as a greater reliance on reuse relative to refurbishment would reduce the labour intensity of turbine and component recovery activities. The economic impacts associated with reinstallation of the turbines and components are not included in this analysis.

3.2.6.3.1 Onshore

3.2.6.3.1.1 Jobs

Figure 49 shows the modelling results for the employment associated with onshore refurbishment across the different scenarios. Employment is higher in the short lifetime scenario, reflecting the assumption within the material flow model that turbines with shorter operational lives are more likely to be suitable for reuse and refurbishment. This increases the volume of components re-entering the onshore refurbishment market, driving additional labour demand.

A +/-50% uncertainty range has been applied across all scenarios to reflect uncertainty in the underlying economic assumptions. Within this range, there is a notable degree of overlap between the BAU and short lifetime scenarios, suggesting that differences between them may be less pronounced in practice. The long lifetime scenario, however, remains more distinct, with comparatively lower refurbishment activity as fewer components are retired and made available for reuse over the modelled period.

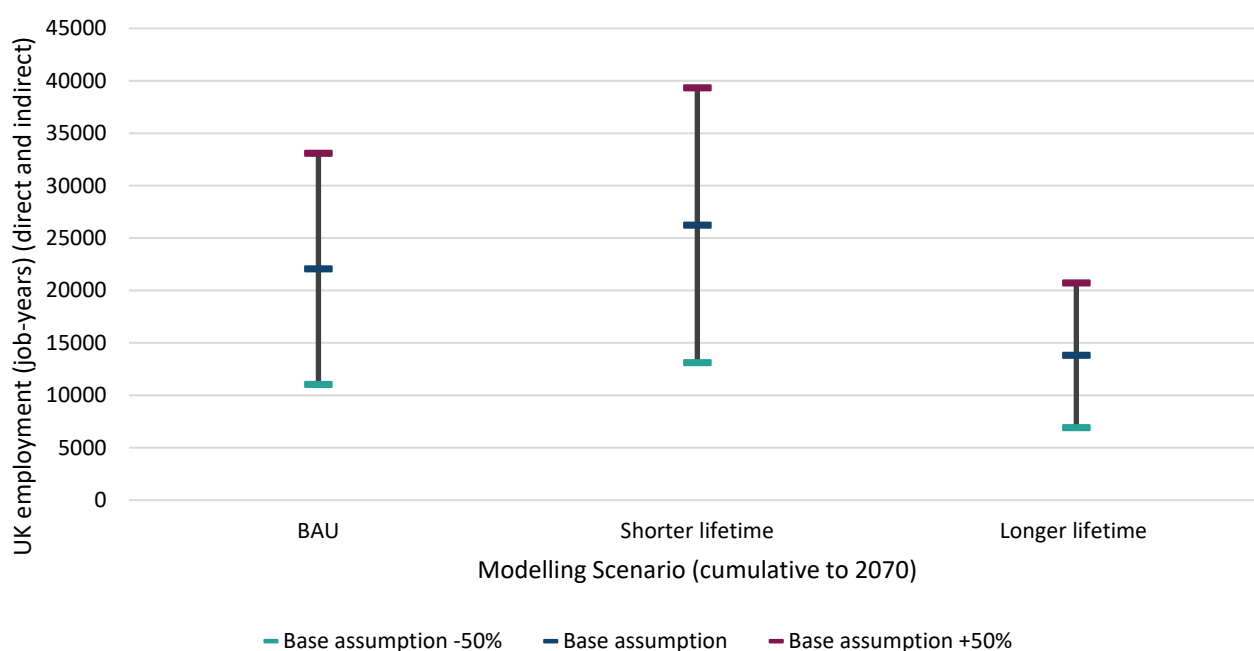


Figure 49: UK employment (job-years) (direct and indirect) associated with onshore refurbishment activities including sensitivity of +/- 50% on economic assumptions (cumulative to 2070)

It is however important to note that this modelling approach assumes a 10% refurbishment rate by total mass across all scenarios. However, findings from the research review suggested that turbines or parts that are retired earlier may not require the same level of refurbishment as older assets, potentially reducing labour intensity and associated job creation. To account for this uncertainty, Figure 50 presents a sensitivity analysis of alternative refurbishment rates across the three scenarios, holding the underlying economic assumptions constant. This demonstrates that outcomes are highly sensitive to refurbishment assumptions.

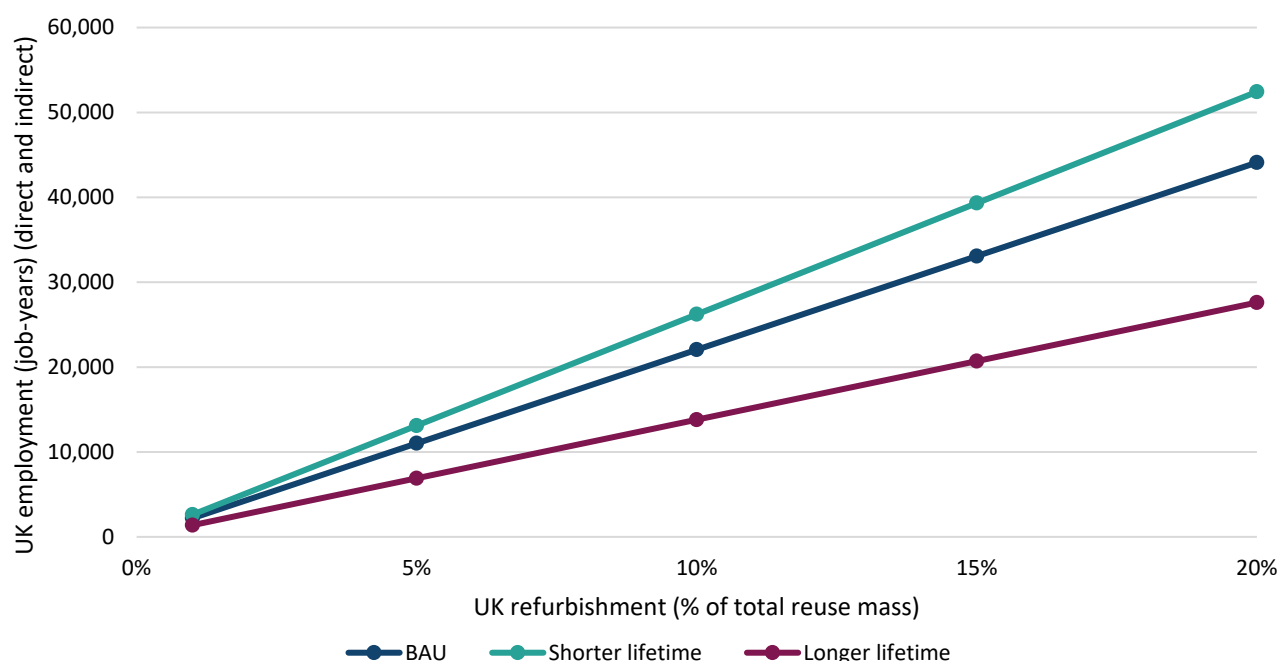


Figure 50: UK employment (job-years) (direct and indirect) associated with refurbishment of turbines and components for reuse (cumulative to 2070) assuming % of UK based refurbishment per total reuse mass of onshore turbines

This highlights that differences in refurbishment rates can be as influential as asset lifetime in determining employment outcomes and reinforces the importance of gathering better evidence on reuse suitability and refurbishment requirements to inform both modelling and policy development.

3.2.6.3.1.2 GVA

Figure 51 shows the UK GVA associated with onshore refurbishment across the different scenarios. The pattern broadly mirrors that of employment, with the short lifetime scenario producing higher GVA due to a greater volume of components entering the refurbishment stream earlier in the modelled period.

A +/- 50% uncertainty range has been applied across all scenarios to reflect uncertainty in the underlying economic assumptions. Within this range, BAU and short lifetime scenarios exhibit considerable overlap, indicating that differences in GVA between them are not especially pronounced once uncertainty is considered. The long lifetime scenario remains more distinct, primarily due to fewer assets reaching end-of-life and therefore reduced refurbishment activity overall.

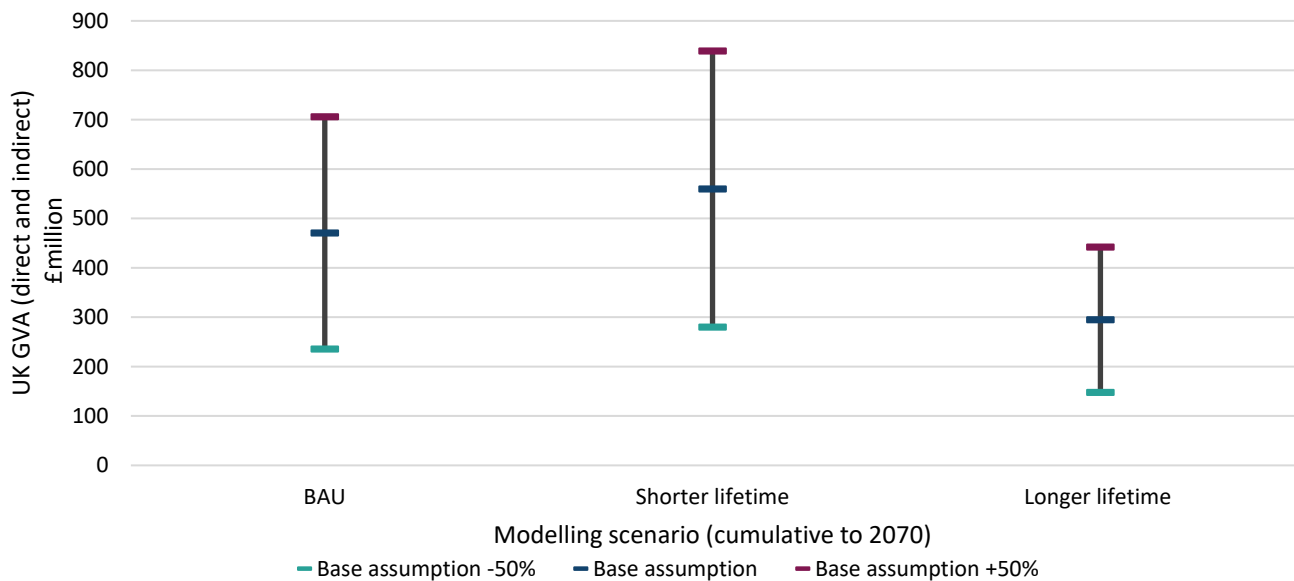


Figure 51: UK GVA (direct and indirect) £million associated with onshore refurbishment activities including sensitivity of +/- 50% on economic assumptions (cumulative to 2070)

As with employment, results are sensitive to assumptions around refurbishment intensity. The modelling assumes a uniform 10% refurbishment rate by total mass, although evidence from the research review suggests that earlier-retired assets may require less intensive intervention. Figure 52 illustrates that increasing the refurbishment rate in the long lifetime scenario to around 20% produces GVA outcomes comparable to a 10% rate in the short lifetime and BAU cases.

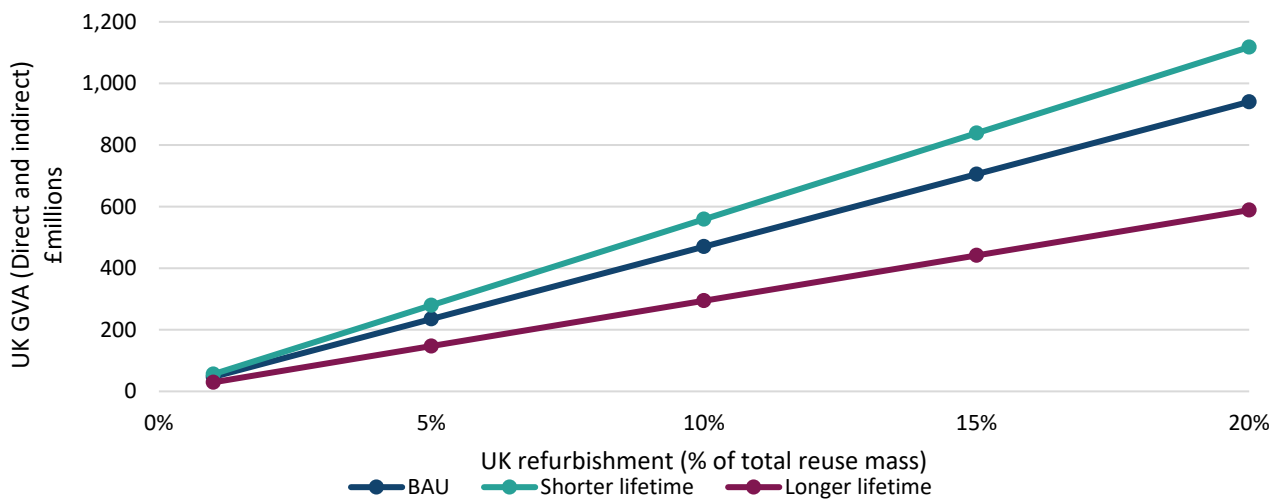


Figure 52: UK GVA (direct and indirect) £millions associated with refurbishment of turbines and components for reuse (cumulative to 2070) assuming % of UK based refurbishment per total reuse mass of onshore turbines

3.2.6.3.2 Offshore

The potential for offshore wind turbine reuse remains highly uncertain, with limited empirical evidence to inform robust assessment. Key unknowns include the structural integrity and remaining fatigue life of major components after prolonged exposure to harsh marine

conditions, as well as the technical and economic feasibility of refurbishing and reinstalling turbines at scale. Market demand for second life turbines is similarly unclear, particularly given rapid technological advancements that may reduce the attractiveness of older equipment. Collectively, these factors mean that projections for offshore turbine reuse are speculative and should be treated with caution in policy and modelling contexts.

3.2.6.3.2.1 Jobs

Figure 53 shows the employment results for offshore wind refurbishment across the different scenarios. As with the onshore case the shorter lifetime scenario is modelled to create the highest employment, largely driven by the underlying assumption that newer turbines and components will be more suited to a second life. However, the +/- 50% range for this value is substantial showcasing the uncertainty associated with this estimate. The overlap between the longer lifetime and BAU scenarios is more pronounced, indicating broadly similar employment outcomes under these assumptions, while the shorter lifetime scenario remains consistently higher across the range of estimates. This differs to the pattern seen in the onshore case, and is driven by differences in the reuse assumptions for the different scenarios as outlined in Table 14.

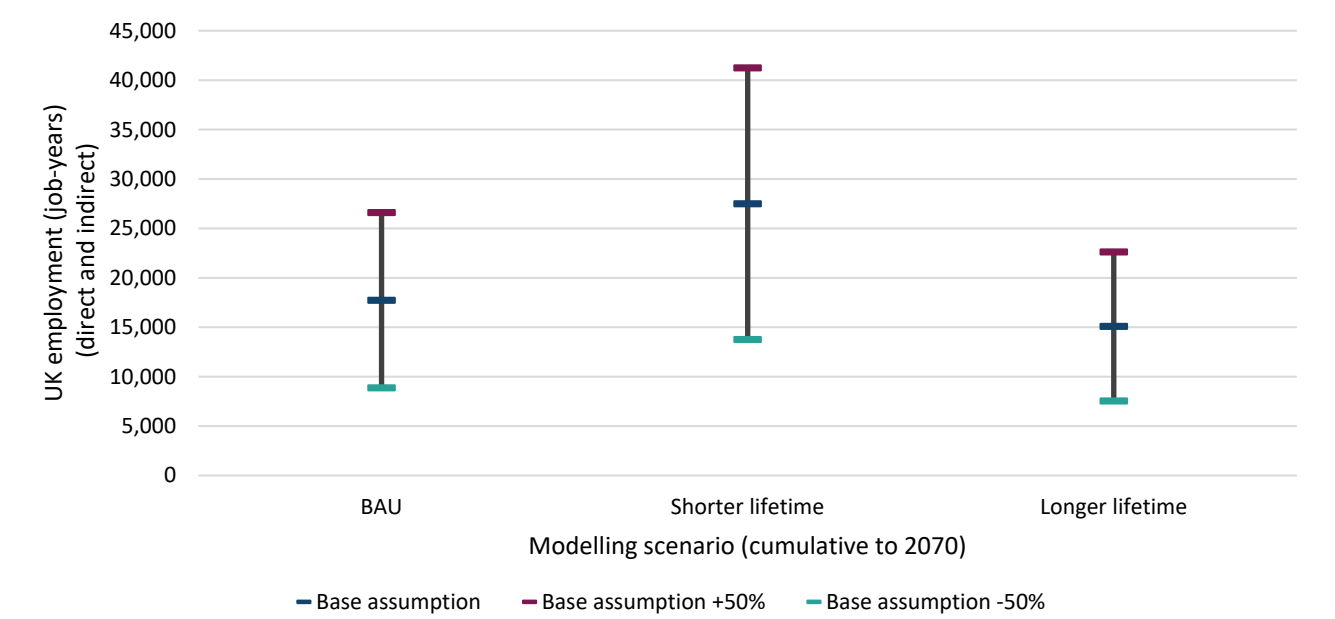


Figure 53: UK employment (job-years) (direct and indirect) associated with offshore refurbishment activities including sensitivity of +/- 50% on economic assumptions (cumulative to 2070)

As with the onshore case, it is important to note that the refurbishment rate has been assumed to be consistent across scenarios at 10% per total reuse mass. This simplifying assumption is applied to isolate the effects of the different lifetime pathways, but in practice refurbishment rates are likely to vary depending on asset age, condition, and the technical feasibility of component recovery offshore. Figure 54 therefore shows the impact of varying this assumption across scenarios. The results demonstrate a clear sensitivity of employment outcomes to changes in refurbishment rates. In particular, the employment impacts associated with a 10% refurbishment rate in both the BAU and longer life scenarios are broadly comparable to those

generated under a 5% refurbishment rate in the shorter life scenario. This highlights that relatively small changes in assumed refurbishment activity can materially shift the scale of employment, underscoring the uncertainty associated with future offshore reuse and refurbishment practices.

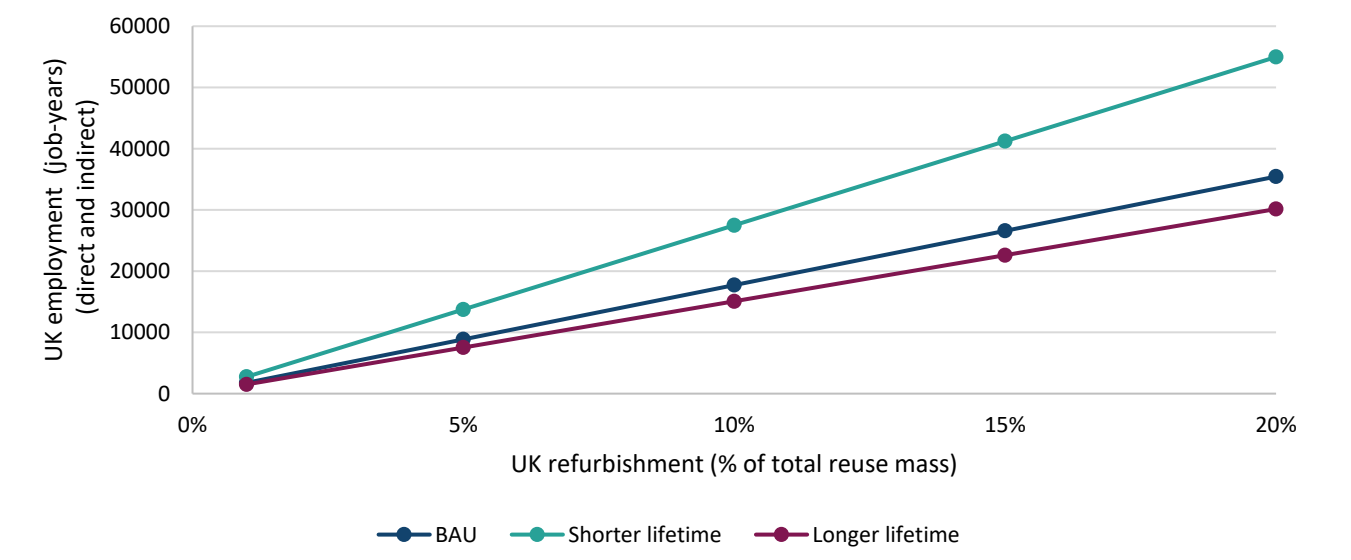


Figure 54: UK employment (job-years) (direct and indirect) associated with refurbishment of turbines and components for reuse (cumulative to 2070) assuming % of UK based refurbishment per total reuse mass of offshore turbines

3.2.6.3.2.2 GVA

Figure 55 shows that the trends for GVA closely mirror those observed for employment impacts, with the shorter life scenario generating the highest overall GVA. However, this result is subject to considerable uncertainty, as reflected in the wide +/- 50% sensitivity range applied to the estimates.

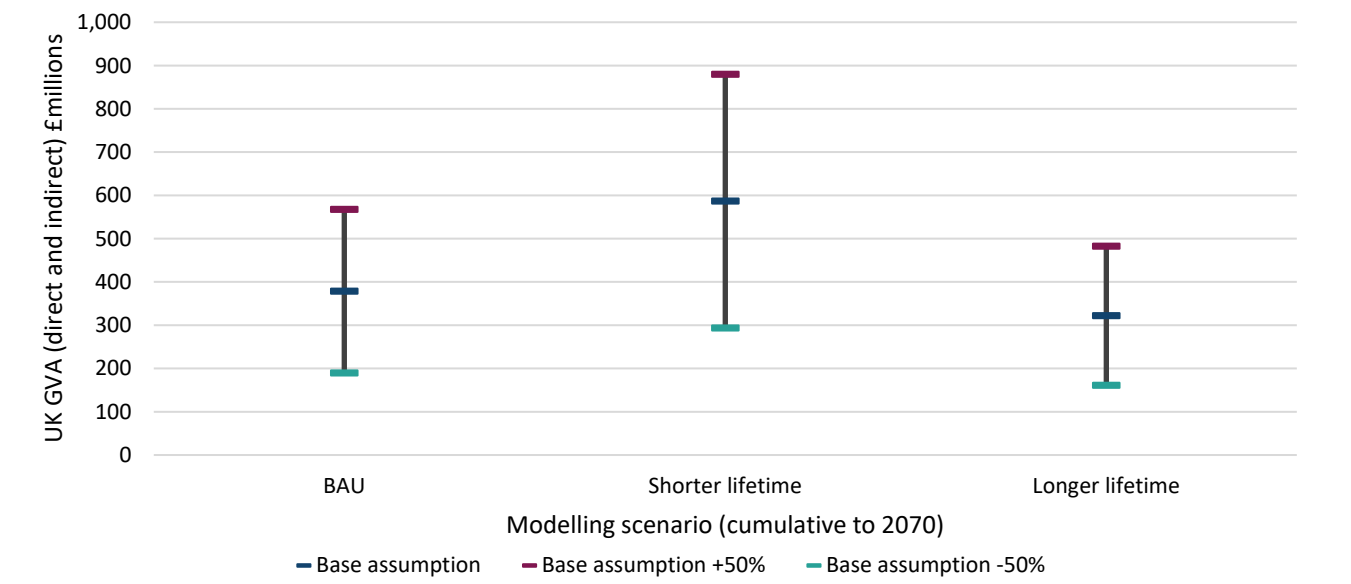


Figure 55: UK GVA (direct and indirect) £million associated with offshore refurbishment activities including sensitivity of +/- 50% on economic assumptions (cumulative to 2070)

As in previous cases, results are sensitive to assumptions around refurbishment intensity. Figure 56 illustrates that a refurbishment rate in the BAU and long lifetime scenario of 10% produces GVA outcomes comparable to a 5% rate in the short lifetime. This indicates that similar levels of economic impact could be realised under different lifetime pathways, depending on the extent of refurbishment activity required. It therefore highlights the degree to which GVA outcomes are driven by assumptions on refurbishment rates rather than lifetime scenario alone.

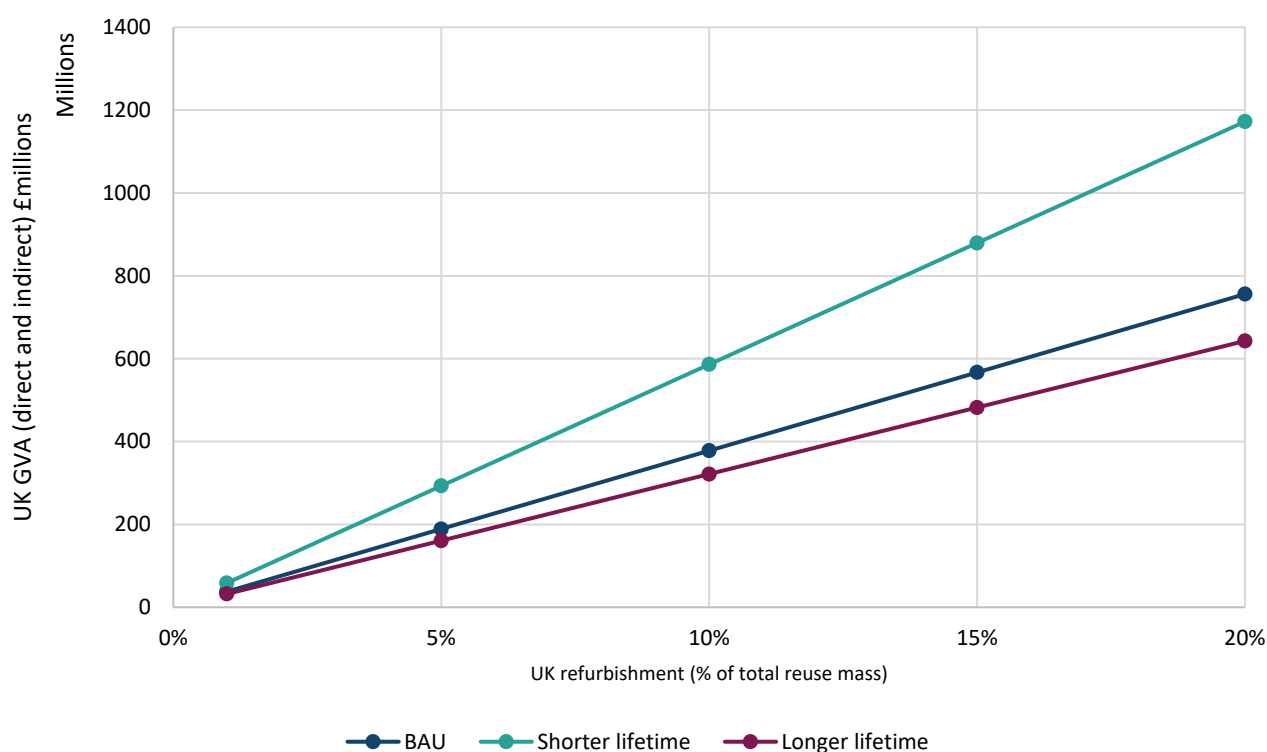


Figure 56: UK GVA (direct and indirect) £millions associated with refurbishment of turbines and components for reuse (cumulative to 2070) assuming % of UK based refurbishment per total reuse mass of offshore turbines

3.2.6.4 Material recovery

Material recovery from wind turbine components is dominated by established mechanical recycling and conventional construction waste treatment routes. For blades, recovery is limited to mechanical processes, as no commercial-scale chemical recycling facilities are currently in operation or planned within the scope of this assessment. In contrast, steel and concrete streams benefit from more mature recycling markets, although recovery outcomes still depend on dismantling practices, transport logistics, and local processing capacity. For scenarios where no material recovery is undertaken and components are assumed to be sent to landfill, no associated economic activity has been modelled. In these cases, both jobs and GVA are assumed to be zero, reflecting the absence of recycling, reprocessing, or secondary material supply chain activity across all material streams.

3.2.6.4.1 Onshore

3.2.6.4.1.1 Jobs

Table 36 illustrates that the employment associated with maximising material recovery follow a similar pattern to the underlying material flows for steel and composite components. The modelling assumes 50% recovery of composites, 50% recovery of concrete and 95% recovery of iron and steel. It should be noted that domestic recovery is currently lower than this maximum, with materials being exported and recovered internationally. In the long lifetime scenario, employment is higher due to a greater proportion of materials being directed into recovery pathways rather than reuse. This reflects the assumption that extended operational lifetimes reduce the suitability of steel and composite components for direct reuse, increasing the volume of material requiring processing, sorting, and recycling. In contrast, concrete-related employment remains consistent across all scenarios. This is because foundations are assumed to follow a single end-of-life pathway, once decommissioned, with all structures fully depleted by 2070 into the material recovery pathway. As a result, there is no variation in concrete-driven employment between scenarios, where it is a significant proportion of the total jobs across all scenarios.

Table 36: UK employment (job-years) (direct and indirect) associated with onshore material recovery activities (cumulative to 2070)

Scenario	UK employment (job-years) (direct and indirect) associated with material recovery activities (to 2070) assuming maximum recovery			
	Steel and iron	Composites	Concrete	Total
BAU	4,800	1,400	4,800	11,000
Shorter	4,300	1,200	4,800	10,300
Longer	5,400	1,500	4,800	11,700

A significant area of uncertainty relates to the proportion of activity that will be retained within the UK supply chain, particularly for steel and composite material recovery. This has a direct influence on the level of domestic jobs generated, as higher levels of export or overseas processing would reduce the economic activity captured within the UK⁷. To reflect this uncertainty, Figure 57 presents a sensitivity analysis of different UK retention rates for material recovery rates for steel and iron, and composites. These results are based on the sensitivities set out in section 3.1.2.3. As the assumed UK retention rate increases, the number of UK based jobs also rises, reflecting the greater share of processing and recovery activity taking place within the domestic supply chain. This relationship is particularly pronounced for steel

⁷ Concrete has been excluded from this sensitivity analysis, as it is assumed that all associated recovery activity is fully localised within the UK. Sensitivity analysis on economic impact of concrete recovery can be found in Appendix C.3 Economic modelling sensitivities

and iron, where increases in retention translate into a steeper uplift in employment compared to composites, largely driven by the associated masses of each material.

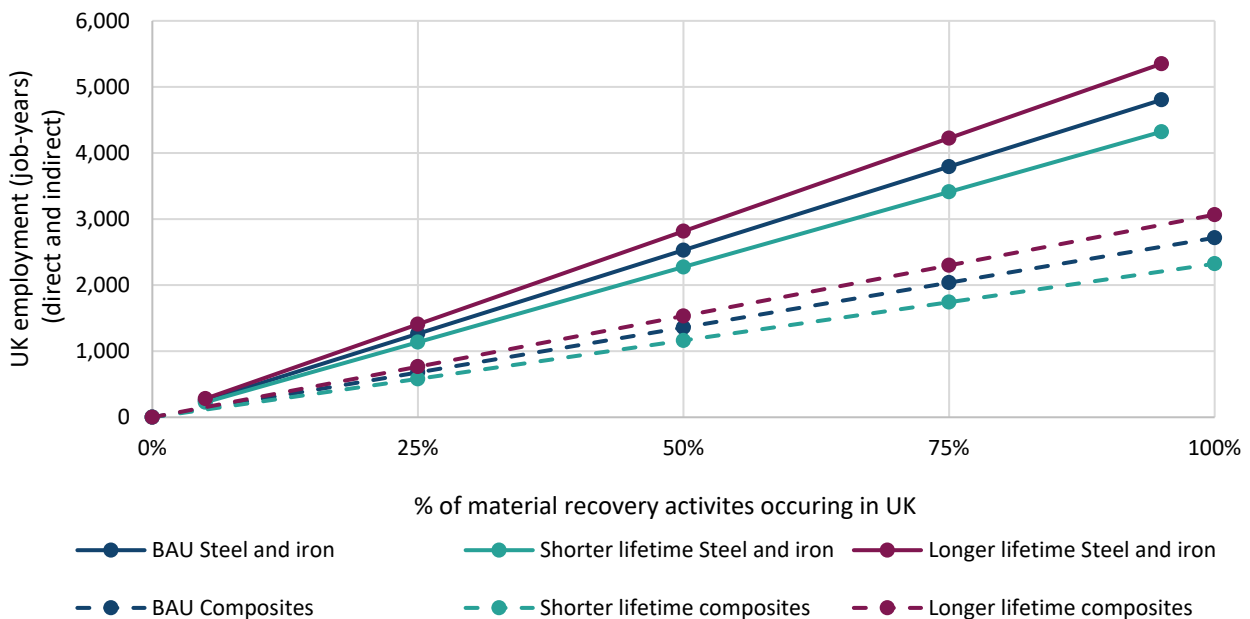


Figure 57: UK employment (job-years) (direct and indirect) sensitivity to % of material recovery activities for steel and iron and composites carried out in the UK for onshore wind (cumulative to 2070)

3.2.6.4.1.2 GVA

Table 37 shows that GVA associated with maximising material recovery follows a broadly similar pattern to employment across all materials. The modelling assumes 50% recovery of composites, 50% recovery of concrete and 95% recovery of iron and steel. It should be noted that domestic recovery is currently lower than this maximum, with materials being exported and recovered internationally. In the long lifetime scenario, GVA is higher due to a greater share of materials being routed into recovery rather than reuse. This reflects the assumption that extended operational lifetimes reduce the suitability of steel and composite components for direct reuse, increasing the volume of material requiring processing, sorting, and recycling activity, and therefore raising associated economic value added. In contrast, GVA associated with concrete remains consistent across all scenarios. This is because foundations are assumed to follow a single end-of-life pathway into material recovery once decommissioned, with all structures fully depleted by 2070. As a result, there is no variation in concrete driven GVA between scenarios.

Table 37: UK GVA (direct and indirect) £millions associated with onshore material recovery activities (cumulative to 2070)

Scenario	UK GVA (direct and indirect) £million associated with material recovery activities (to 2070) assuming maximum recovery			
	Steel and iron	Composites	Concrete	Total
BAU	515	95	340	950
Shorter	465	80	340	885
Longer	575	105	340	1,020

As with employment, Figure 58 illustrates that the GVA is highly dependent on the percentage of material recovery activities that take place within the UK. This relationship is particularly pronounced for steel and iron, where increases in retention translate into a steeper uplift in employment compared to composites, largely driven by the associated masses of each material. While the overall trend mirrors that observed for employment, the relative contributions differ slightly. Composites account for a smaller share of total GVA than they do for jobs, reflecting differences in processing value and economic intensity across material types. It should be noted that limited information is currently available on the GVA associated with composite material recovery, therefore this relies on more generic material recovery assumptions.

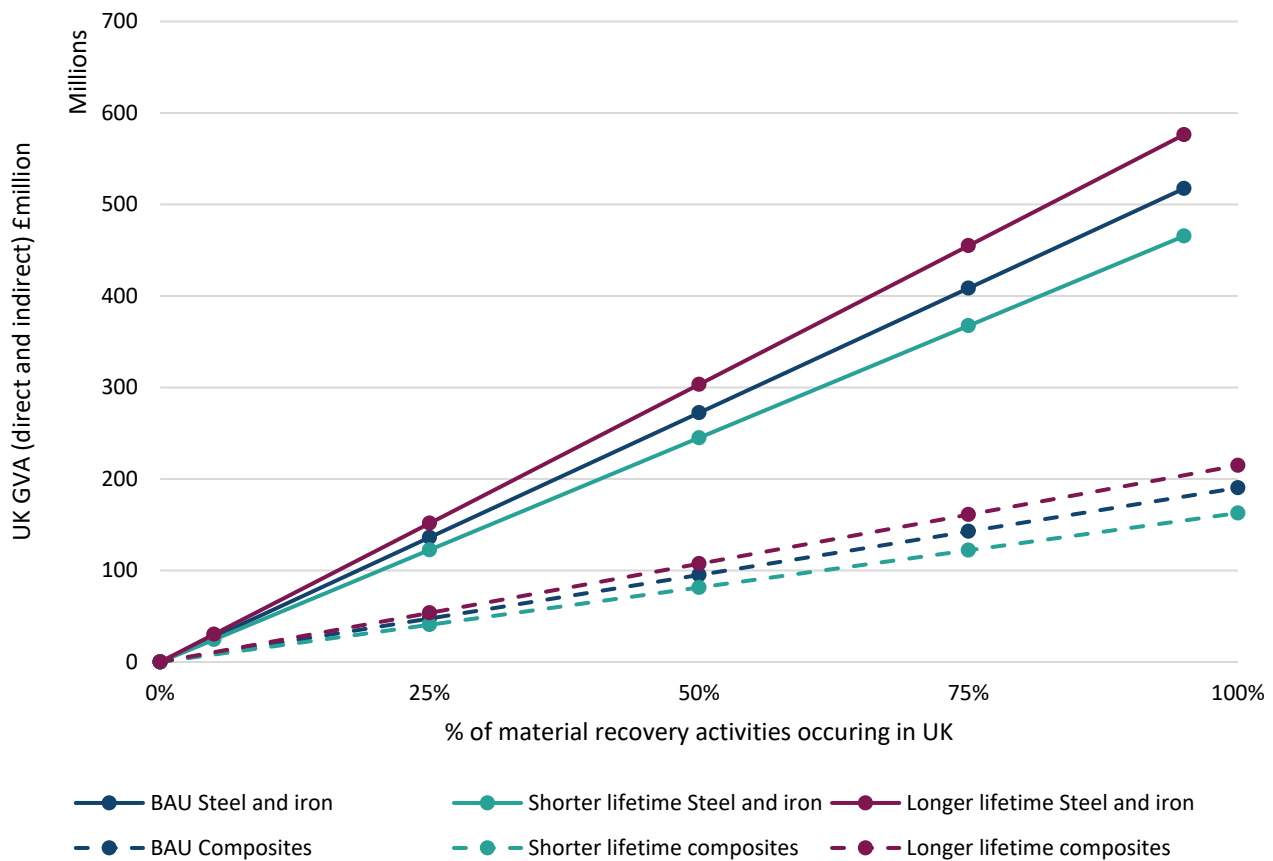


Figure 58: UK GVA (direct and indirect) £million sensitivity to % of material recovery activities for steel and iron and composites carried out in the UK for onshore wind (cumulative to 2070)

3.2.6.4.2 Offshore

3.2.6.4.2.1 Jobs

Table 36 illustrates that the employment associated with material recovery follow a similar pattern to the underlying material flows for steel and composite components. In the long lifetime scenario, employment is higher due to a greater proportion of materials being directed into recovery pathways rather than reuse. This reflects the assumption that extended operational lifetimes reduce the suitability of steel and composite components for direct reuse, increasing the volume of material requiring processing, sorting, and recycling

Table 38: UK employment (job-years) (direct and indirect) associated with offshore material recovery activities (cumulative to 2070)

Scenario	UK employment (job-years) (direct and indirect) associated with material recovery activities (cumulative to 2070) assuming maximum recovery		
	Steel and iron	Composites	Total
BAU	19,700	2,900	22,600
Shorter	19,000	2,400	21,400
Longer	20,000	3,200	23,200

Figure 59 presents a sensitivity analysis of different UK retention rates for material recovery rates for steel and iron, and composites. These results are based on the sensitivities set out in section 3.1.2.3. As the assumed UK retention rate increases, the number of UK based jobs also rises, reflecting the greater share of processing and recovery activity taking place within the domestic supply chain. This relationship is particularly pronounced for steel and iron, where increases in retention translate into a steeper uplift in employment compared to composites, largely driven by the associated masses of each material.

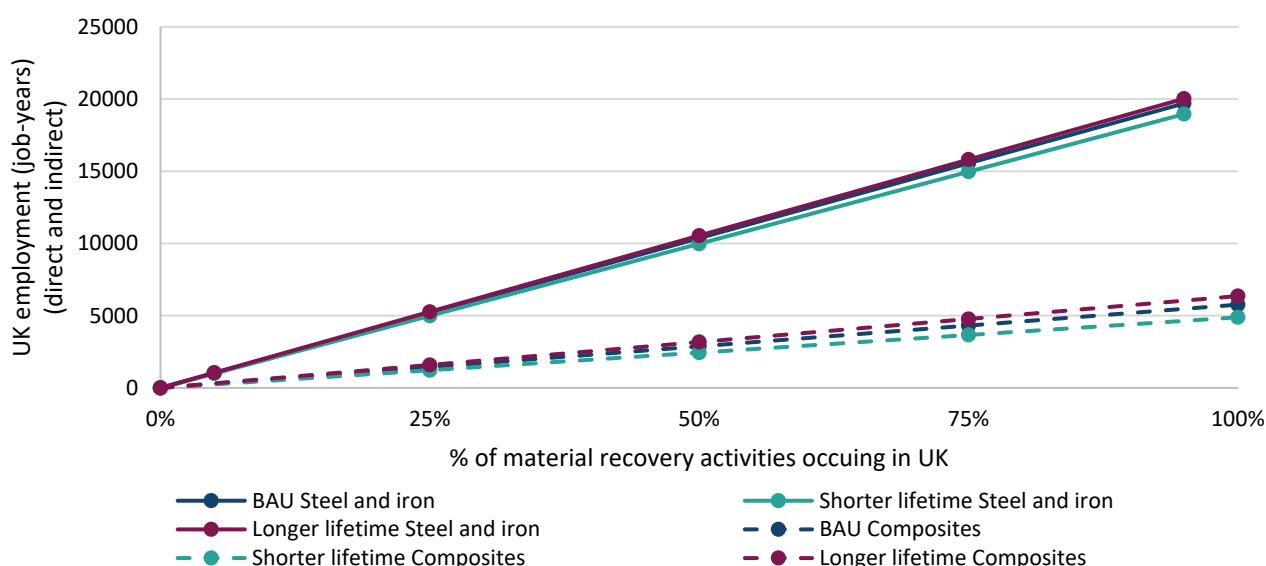


Figure 59: UK employment (job-years) (direct and indirect) sensitivity to % of material recovery activities for steel and iron and composites carried out in the UK for offshore wind (cumulative to 2070)

3.2.6.4.2.2 GVA

Table 39 shows that GVA associated with material recovery follows a broadly similar pattern to employment across all materials, with only relatively modest variation between scenarios. This

reflects the fact that material recovery activities are largely driven by the same underlying volumes of recovered steel, iron, and composite materials. As a result, while scenario assumptions do influence the distribution of activity, the aggregate GVA remains broadly stable across the modelling range.

Table 39: UK GVA (direct and indirect) £millions associated with offshore material recovery activities (cumulative to 2070)

Scenario	UK GVA (direct and indirect) associated with material recovery activities (to 2070) (£million) assuming maximum recovery		
	Steel and iron	Composites	Total
BAU	2,100	200	2,300
Shorter	2,000	170	2,170
Longer	2,200	220	2,420

Figure 60 shows the impact of varying the proportion of material recovery activity captured within the UK. As the assumed UK share increases, total GVA rises accordingly, reflecting the greater retention of economic value within the domestic supply chain. Steel and iron recovery contributes significantly more to GVA than composite materials. This is primarily due to the much larger volumes involved, as well as more established recycling infrastructure and higher levels of economic activity associated with metal processing. In contrast, composite recovery remains a smaller contributor to overall GVA, reflecting both lower material volumes and the more limited scale and maturity of current recycling pathways for these materials.

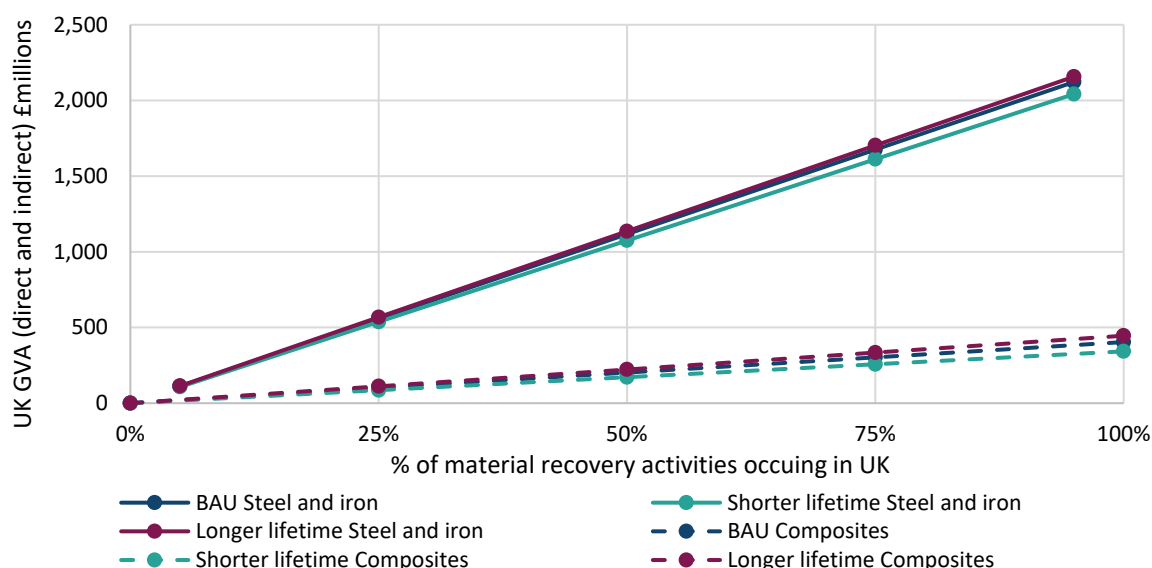


Figure 60: UK GVA (direct and indirect) £million sensitivity to % of material recovery activities for steel and iron and composites carried out in the UK for offshore wind (cumulative to 2070)

3.2.6.5 Operations and Maintenance

Although O&M activities extend beyond repair and recovery, they provide valuable insights into the wider economic impacts associated with life extension. However, jobs and GVA estimates provided in literature are typically presented at an aggregated level. As a result, these figures often include MCE, therefore the analysis in this section should not be considered alongside the MCE impacts in section 3.2.6.1 as this may result in double counting of impacts.

3.2.6.5.1 Onshore

3.2.6.5.1.1 Jobs

Literature provides a range of estimates for the number of O&M jobs associated with onshore wind, typically spanning from around 56 to 110 FTE per GW of installed capacity. This variation reflects differences in assumptions around turbine size, site characteristics, maintenance strategies, and the extent of local supply chain involvement.

Table 40: Onshore O&M FTE per GW ratios found in literature

Onshore O&M FTE per GW ratios derived from literature		
Low	Chosen	High
56	88	110

Figure 61 presents the modelling results using three representative assumptions within this range (Table 40) applied consistently across each of the three scenarios (BAU, shorter lifetime, longer lifetime). This allows for a comparison of how sensitive overall employment outcomes

are to underlying O&M intensity, alongside the differences driven by asset lifetime assumptions. It can be seen that there is a significant overlap between the BAU and longer lifetime scenarios, reflecting the similarity in their operational timelines and the point at which assets begin to exit service. In contrast, the shorter lifetime scenario diverges more noticeably, driven by earlier decommissioning which reduces the duration over which O&M employment is sustained.

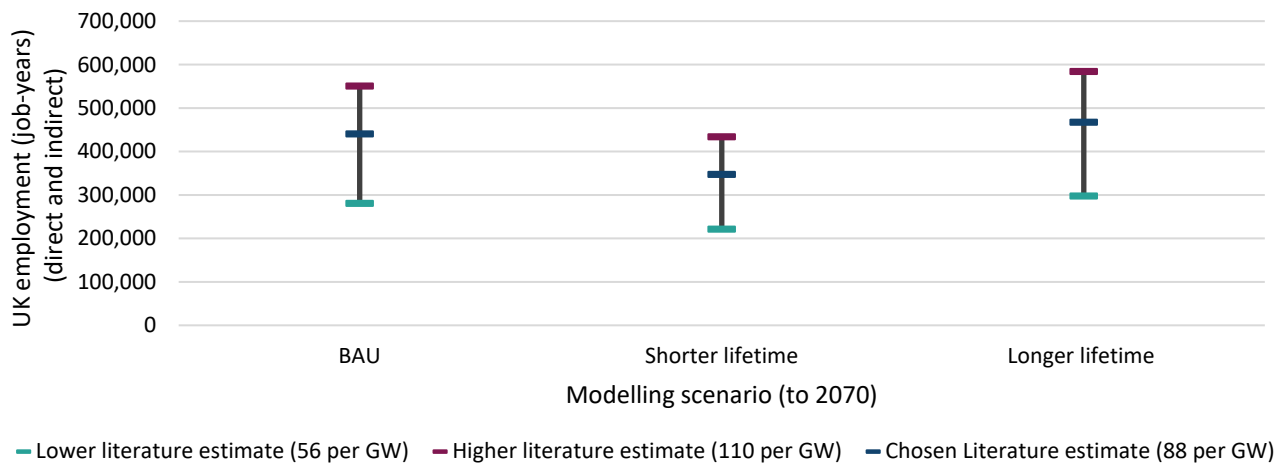


Figure 61: UK employment (job-years) (direct and indirect) associated with onshore O&M activities (cumulative to 2070) including sensitivity based on assumptions found in literature

The total number of jobs associated with O&M is significantly larger than those linked to repair and material recovery activities explored in this section. However, the majority of these roles are common across all scenarios, as they are driven primarily by the installed capacity in operation rather than end-of-life assumptions.

As a result, Figure 62 presents the relative number of jobs compared to the BAU scenario, providing a clearer view of how differences in decommissioning timelines and asset lifetimes influence O&M employment. This highlights how life extension can sustain O&M roles for longer, while the shorter lifetime shows declines in associated employment. This illustrates the importance of considering the wider system impacts when making decisions around asset lifetimes. While repair and recovery activities may increase under shorter lifetimes, these need to be weighed against potential reductions in longer-term O&M employment, reinforcing the need for a whole lifecycle perspective.



Figure 62: Onshore O&M employment (job-years) (direct and indirect) for shorter and longer lifetimes relative to BAU (cumulative to 2070) for different economic assumptions

3.2.6.5.1.2 GVA

The range of jobs ratios obtained from literature (Table 40) have been converted into GVA estimates based on the assumptions set out in Appendix C.1 Economic modelling methodology. The results of the modelling are shown in Figure 63. The trend follows that of the employment impacts, with significant overlaps between BAU and the longer life scenario and a marked reduction in GVA associated with the shorter lifetime scenario.

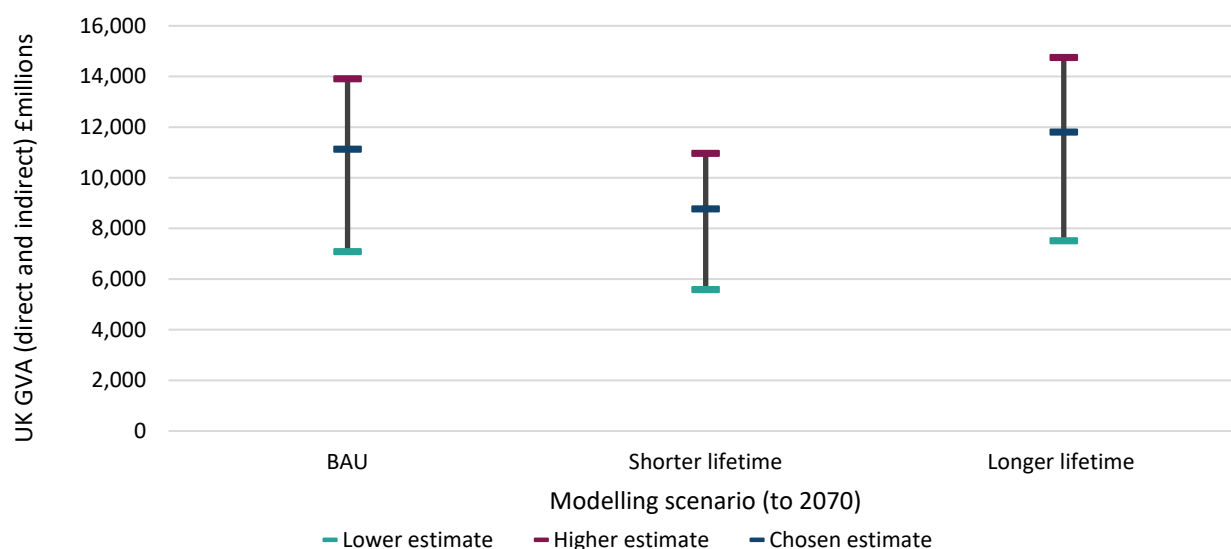


Figure 63: UK GVA (direct and indirect) £millions associated with onshore O&M activities (cumulative to 2070) including range of assumptions found in literature (cumulative to 2070)

To account for the majority of O&M GVA being related to the operational life phase of the wind turbine, Figure 64 shows the GVA for the longer and shorter lifetime relative to the BAU scenario. The shorter scenario shows the most significant deviation from the BAU across all economic assumptions.

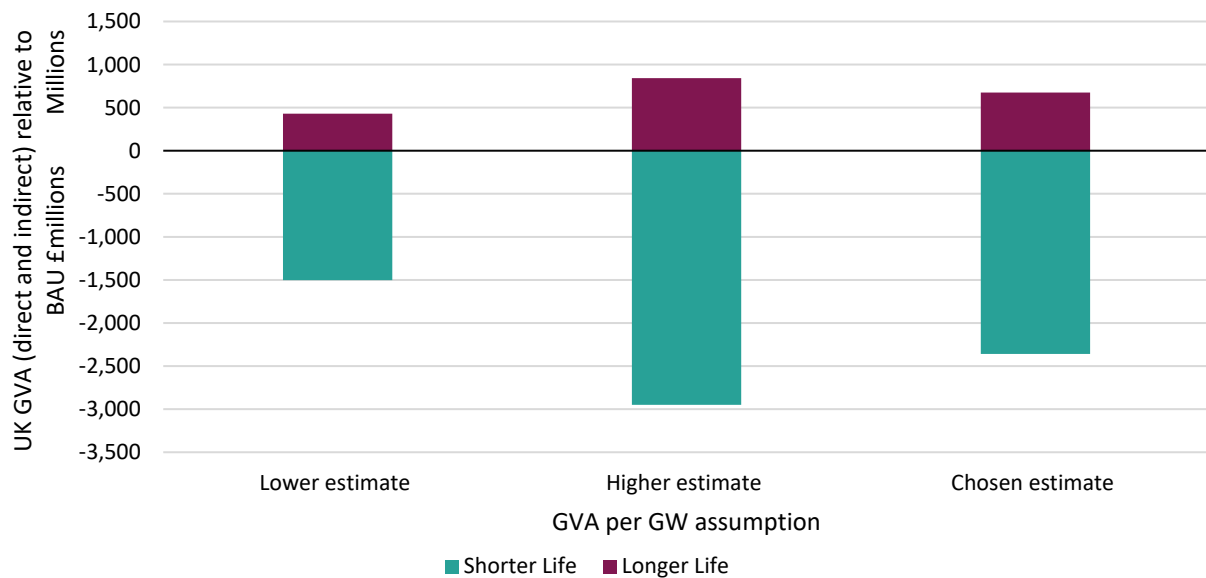


Figure 64: UK GVA (direct and indirect) £million for shorter and longer lifetimes relative to BAU (to 2070) for different economic assumptions

3.2.6.5.2 Offshore

3.2.6.5.2.1 Jobs

Figure 65 provides the employment estimates associated with offshore O&M activities, these roles significantly outweigh the jobs associated with repair and recovery activities, reflecting the scale and duration of operational offshore wind activity relative to end-of-life interventions. The estimates are based on a single underlying data point, and therefore a +/-50% sensitivity has been applied to reflect the uncertainty associated with this assumption. As a result, there is a significant degree of overlap between scenarios, driven by the wide confidence range rather than differences in underlying activity levels. Nevertheless, the longer lifetime scenario produces the highest employment outcomes, owing to the extended operational period and consequently greater cumulative O&M requirements. It should also be noted that any potential increase in O&M intensity associated with ageing assets has not been explicitly captured within the modelling. As such, differences between scenarios may be more pronounced in practice than currently reflected in the results.

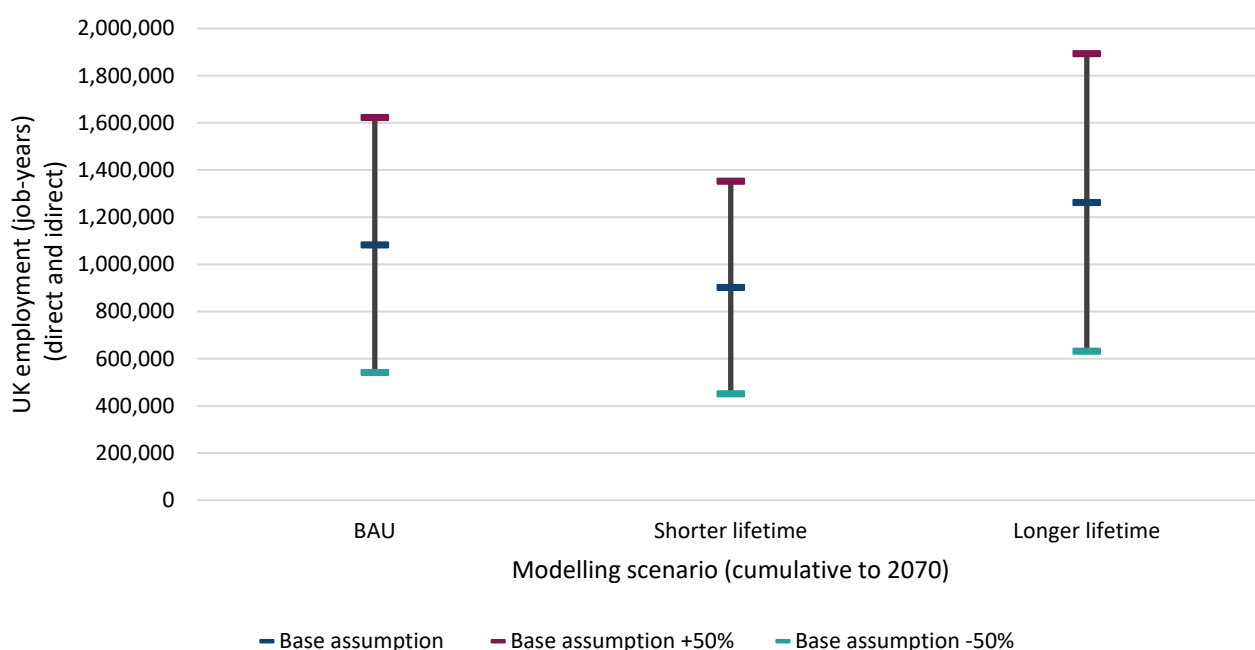


Figure 65: UK employment (job-years) (direct and indirect) associated with offshore O&M activities (cumulative to 2070) including +/- 50% sensitivity on economic assumptions

3.2.6.5.2.2 GVA

The trend for GVA closely mirrors that observed for employment, with both following the same relative pattern across scenarios. As with employment, the longer lifetime scenario generates the highest overall GVA due to the extended period of operational activity, while the shorter lifetime scenario produces lower cumulative values. However, the magnitude of variation between scenarios remains sensitive to the underlying assumptions used.

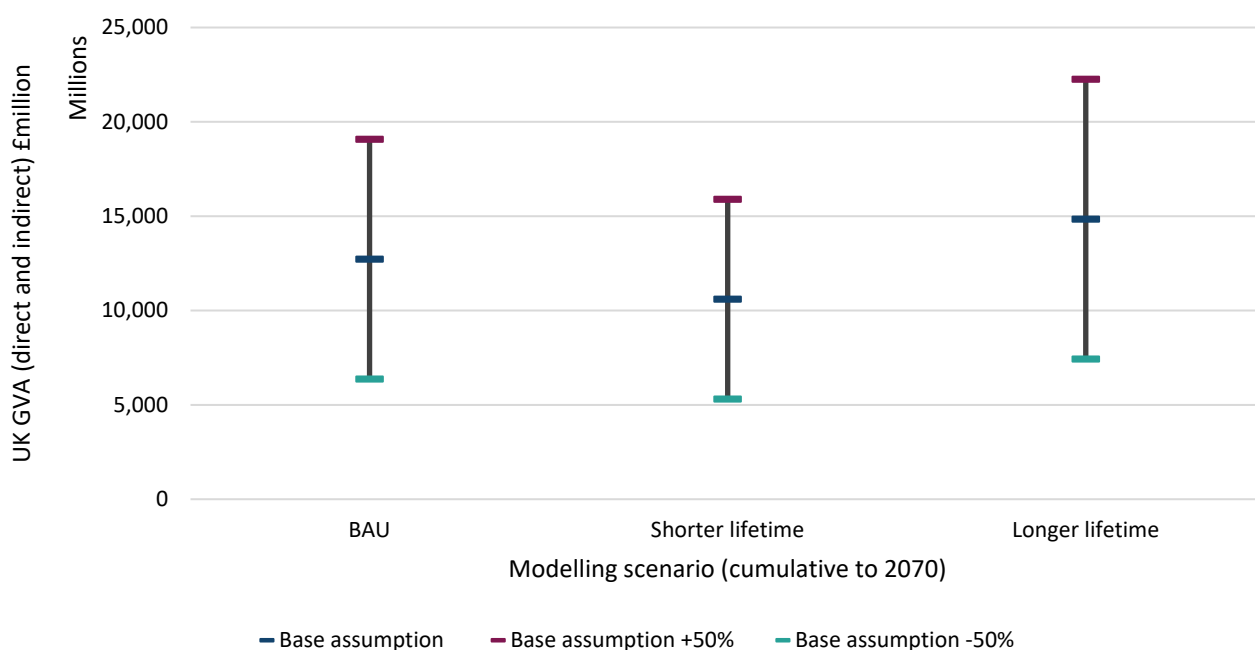


Figure 66: UK GVA (direct and indirect) £millions associated with offshore O&M activities (cumulative to 2070) +/- 50% sensitivity on economic assumptions

3.2.7 RQ2b: What is the best use of recovered materials and components?

Based on the results from the emissions impact assessment (Section 3.2.3) and the economic impact assessment (Sections 3.2.5 and 3.2.6), this section suggests the best use of material following decommissioning from a wind farm asset. These results are highly dependent on the outputs from the material flow modelling, which defines how much material is reused, recycled and not recovered for each lifetime scenario and sensitivity analysis.

3.2.7.1 Emissions impact assessment

The emissions modelling (Section 3.2.3) suggests that increasing the material reuse fraction of steel and iron (generator and gearbox mass) and composites (blade mass) reduces the total emissions per energy generation for all scenarios for both onshore and offshore. As the reuse fraction is increased by 20% from the baseline material handling ratios (Section 3.1.2.2) total emissions per energy generation decreased by up to 2.29 and 1.31 tonnes CO₂e per GWh for onshore and offshore wind, respectively.

Composite and concrete material recovery have a minimal impact the total emissions per energy generation, with a reduction of less than 0.25% for all scenarios as recovery increases from 0% to 100% for both onshore and offshore wind.

However, steel and iron material recovery has a significant impact on the model outputs. As the recovery ratio increases from 5% to 75%, the net emissions impact decreases for both onshore (up to 2.15 t CO₂e/GWh) and offshore wind (up to 4.24 t CO₂e/GWh).

To maximise emissions reductions, life extension should be considered along with increased component reuse and steel and iron material recovery.

3.2.7.2 Economic impact assessment

When considering the best handling pathway for materials and components, the economic analysis indicates that refurbishment of wind components generally provides greater employment and GVA benefits than material recovery alone, although the relative contribution varies across scenarios due to differing reuse assumptions. Refurbishment activities are typically more labour-intensive and retain a greater proportion of the embedded value within components, leading to higher economic impacts per unit of material processed.

The economic results are highly sensitive to the assumed refurbishment rate. Sensitivity analysis showed that relatively small changes in the proportion of components directed towards refurbishment can materially alter both employment and GVA outcomes. For example, a 5% increase in refurbishment rates resulted in approximately 50% higher employment and GVA across the assessed scenarios. In some cases, higher refurbishment assumptions within the BAU or longer lifetime scenarios generated economic impacts comparable to lower refurbishment assumptions in the shorter lifetime scenario.

Across the onshore scenarios assessed, refurbishment was estimated to support approximately 14,000–26,000 jobs, compared with around 10,000–12,000 jobs associated with

material recovery activities. Whilst the GVA values were £300-£560 million and £890-£1,020 million respectively. This suggests that, where technically feasible, prioritising refurbishment and second-life applications could maximise the economic value retained from end-of-life wind assets.

However, material recovery remains a necessary and strategically important component of the end-of-life pathway. Large structural elements such as towers and foundations have limited or no viable reuse potential at scale, with reuse generally restricted to whole-turbine applications. This reinforces the importance of developing robust domestic capability in material recovery and recycling, particularly for steel and concrete, to ensure value is retained within the UK economy where refurbishment is not feasible.

4 Conclusion

4.1.1 RQ 1a: To what extent can repair and maintenance help extend the lifetime of existing wind turbines?

The literature review showed that advances in condition monitoring, digital diagnostics, and intelligent maintenance systems improve operators ability to assess turbine health and support lifetime extension decisions. These tools will become increasingly important as turbines grow larger and more complex. However, significant data gaps remain, particularly in relation to component failure, repair, and replacement rates, which are not consistently captured or shared. This limits the ability to quantify lifetime extension potential across the fleet. Wider factors, including skills availability, land ownership, leasing arrangements, and policy certainty also influence feasibility. While repair and maintenance can enable meaningful lifetime extension, the duration for extension tends to depend less on turbine age and more on turbine design, spare part supply chains, data quality, and the wider economic and regulatory context in which assets operate.

Similarly, stakeholder interview findings showed that while repair and maintenance play a key role in extending the operational lifetime of wind assets, lifetime extension is highly variable and dependent on individual site and asset conditions. Turbine design life was commonly defined as 20–25 years, however both the literature and industry practice demonstrate that actual operational lifetimes can vary significantly. Outcomes are shaped by a combination of factors, including regulatory requirements, turbine condition, operational history, environmental conditions, maintenance strategies, and wider policy and market settings. Regulatory frameworks for lifetime extension are seen in countries such as Germany and Denmark, whereas the absence of specific UK guidance has resulted in a more case-by-case approach. For offshore wind, additional challenges arise from the separation of ownership between wind farms and transmission assets, creating risks where life extension of generation and grid infrastructure are not immediately aligned.

Stakeholder interviews indicate that lifetime extension is already standard practice across much of the UK onshore wind fleet, with extensions of 5–10 years beyond original design life widely reported and several sites already operating beyond 30 years. Decisions on whether to extend typically begin well before the end-of-design life is reached, with assessments being carried out in years 17–20 for onshore wind, and potentially even earlier for offshore wind. Decisions are driven more by economic viability and component availability than by age alone. There is currently no dedicated financial support mechanism specifically targeted at enabling or incentivising life extension activities, with projects instead relying on prevailing market revenues and asset-level economics. Access to spare parts emerged as the most critical enabling factor. As turbine models age, OEM support often reduces, resulting in increased costs, lead times, and reliance on refurbished components. In practice, the speed and availability of parts frequently outweigh whether components are new or refurbished.

The information from the literature review and stakeholder interviews was used as an input to the material flow model, in addition to further research completed during the quantitative modelling into component failure and replacement rates. For the expected fleet lifetime, three lifetime scenarios were formulated: a BAU scenario, a shorter lifetime scenario, and a longer lifetime scenario. For offshore wind, 30 years was used for BAU, reducing to 25 years for shorter lifetime and increasing to 35 years for longer lifetime, based on the research review. For the BAU scenario of onshore wind, a Weibull function was fitted to the ratios of decommissioned to installed capacity by installation year of the UK onshore fleet. This corresponds to a depletion function in which 50% of the fleet is expected to be decommissioned after approx. 32 years. The shorter and longer lifetime scenarios are based on this BAU function and shifted to reflect different market developments, with 50% decommissioning reached after approx. 25 and 34 years, respectively.

With the current available information, it was not possible to quantify the relationship between O&M and the possible lifetime extension of wind turbines. The feasibility of a longer lifetime also depends on factors such as spare parts availability, development of revenues for selling the generated power and land lease agreement. In this regard, refurbishment and remanufacturing capacities are important as well as improved O&M practices, e.g. use of smart data to enable predictive maintenance. Further research is recommended to better understand technical limits and develop technologies to enable lifetime extensions of the existing fleet and future installations.

Given the remaining research gaps and uncertainties of future developments, this study applied constant failure rates per turbine per year. When further data becomes available, it is highly recommended to introduce rates that account for the different turbine designs, different O&M practices and the age of the turbine and its subsystems over time. In addition, the consideration of component replacements to extend the turbine's lifetime such as converters (e.g. Anderson, 2024) or other updates, upgrades or retrofits would be relevant to consider in future analyses.

4.1.2 RQ 1b: What is the net impact on material demand associated with extending the lifetime of wind assets?

Findings from the literature review and stakeholder interviews suggested that the impact of wind turbine lifetime extension on material demand is unclear, with a relatively thin evidence base to build upon. The stakeholder interviews found that minimal evidence is routinely gathered by any part of the industry or supply chain on the materials or emissions impact of life extension. However, life extension will require significantly less material demand than repowering a site with new wind turbines would. The effect on resource security in the UK is, nevertheless, likely to be limited due to low domestic wind manufacturing capacity. In the medium to short term, extending the operational lifetime of wind assets can reduce primary material demand. However, these savings are strongly context-dependent and diminish under high deployment growth, meaning lifetime extension delays rather than eliminates material demand.

The quantitative modelling shows that the largest material demand is associated with the initial installation of the wind assets and is therefore independent of the associated wind assets' lifetime. Material demand for component replacements - modelled in this study for generators, gearboxes, and blades - increases with extended asset lifetimes, as replacements also occur during the prolonged operational phase.

For installing the onshore wind turbine fleet from 1990-2027, the demand for the material in scope is approximately 12.8 Mt. Concrete made up 77.5% of the total, 20.9% was from steel and iron, and only 1.6% was from composites. For onshore wind component replacements during the operational phase, the estimated material demand for BAU scenario was 0.8 Mt, shorter lifetime was 0.6 Mt, and longer lifetime required 0.8 Mt. Across all scenarios, steel and iron contributed to 81% of the component replacements and 19% was from composites, while no foundation (mainly concrete) is replaced during operation. Offshore wind required an estimated 11.0 Mt of installation material for all scenarios. Broken down into specific materials, steel and iron made up 96.5% of the total, 3.2% was from composites, and only 0.3% was from concrete. In contrast to onshore, significant quantities of steel and iron are also required for the offshore foundation/substructure, while concrete is currently only used in the foundation of one offshore wind project. Concrete may become more relevant for offshore should the technology be adopted for floating wind platforms. For offshore wind component replacements, the estimated material demand for BAU scenario was 0.9 Mt, shorter lifetime was 0.7 Mt and longer lifetime required 1.0 Mt. Across all scenarios, steel and iron contributed to 64% of the component replacements and 36% was from composites.

When comparing the onshore wind material demand for each scenario in terms of energy generation, the longer lifetime scenario (10.15 t/GWh) has the lowest material demand per energy generated, followed by BAU (10.73 t/GWh) and then shorter lifetime (13.45 t/GWh). From short to long lifetime, total installation and component replacement material demand increases by 1.5%, while energy generation increases by 34.1%. The offshore wind material demand in terms energy generation shows a similar trend as onshore, the longer lifetime scenario (3.90 t/GWh) has the lowest material demand per energy generated, followed by BAU (4.49 t/GWh) and then shorter lifetime (5.32 t/GWh). From short to long lifetime, total installation and component replacement material demand increases by 1.5%, while energy generation increases by 39.6%.

Regardless of the replacement rate sensitivity, the longer lifetime scenario remains the most effective scenario, maintaining the lowest material demand per energy generation for both onshore and offshore wind.

4.1.3 RQ 1c: What is the net impact on emissions associated with extending the lifetime of existing onshore and offshore wind assets?

The literature review identified various research papers that have assessed the potential impact of wind turbine lifetime extension. Several LCAs discussed life extension, although many treated it as part of a sensitivity analysis and not as a primary research focus. Extending turbine lifetimes typically reduced emissions per energy generation. Extending the lifespan of

turbines, especially through component refurbishing and material recycling, was typically estimated to reduce carbon footprints significantly. However, the level of detail within each analysis was unclear. There was also a lack of comprehensive data on circular economy strategies in offshore wind, especially on reuse, refurbishing, lifetime extension and decommissioning, suggesting a need for further research. It was found that lifetime extension, partial repowering, repair and recycling are crucial for reducing emissions, but further research is needed to refine lifecycle assessment methods and to better understand long-term environmental benefits of these strategies.

The stakeholder interviews found that minimal evidence is routinely gathered by any part of the industry or supply chain on the materials or emissions impact of life extension. One exception was an asset owner which stated it is starting to track emissions savings from its activities, with the anticipation this data may be used by stakeholders involved in the offshore consenting process. A long operating life was also identified by one stakeholder as an opportunity to reduce the “carbon cost” of power generation.

The emissions modelling suggests that life extension reduces the net impact on emissions as wind fleet lifetime is extended. For onshore wind, longer lifetime produces the lowest emissions per energy generation (15.65 t CO₂e/GWh), followed by BAU (15.82 t CO₂e/GWh) and then shorter lifetime (18.82 t CO₂e/GWh). Similarly for offshore wind, longer lifetime produces the lowest emissions per energy generation (14.92 t CO₂e/GWh), followed by BAU (16.74 t CO₂e/GWh) and then shorter lifetime (18.98 t CO₂e/GWh). Although more materials and operations emissions are produced (onshore 1.4 Mt CO₂e, offshore 3.3 Mt CO₂e) for the increased component replacements in the longer lifetime when compared to shorter lifetime, the increased energy generation (onshore 3.41x10⁵ GWh, offshore 8.8x10⁵ GWh) offsets the additional emissions.

To further reduce total emissions per energy generation, increasing both component reuse and steel and iron material recovery should be considered. For onshore and offshore wind, increasing the material reuse fraction by 20% decreases emissions per energy generation by up to 2.29 and 1.31 tonnes CO₂e per GWh, respectively. Increasing steel and iron material recovery from 5% to 75% decreases the net emissions impact for onshore (2.15 t CO₂e/GWh) and offshore wind (4.24 t CO₂e/GWh). Composite and concrete material recovery have a minimal impact on the total emissions per energy generation, with a reduction of less than 0.25% for all scenarios as recovery increases from 0% to 100% for both onshore and offshore wind. For all sensitivity analysis results, the longer lifetime scenario remains the most effective scenario, maintaining the lowest total emissions per energy generation for both onshore and offshore wind. To maximise emissions reductions, life extension should be considered along with increased component reuse and steel and iron material recovery.

4.1.4 RQ 2a: How much material and reusable components can be recovered from existing onshore and offshore wind assets?

From the stakeholder interviews, there was a consensus that for onshore assets, reuse of turbines is being increasingly considered as a desirable and realistic option for asset owners

undertaking a decommissioning project. Information on the typical process for offshore wind was more limited.

When whole turbine resale is not feasible, asset owners prioritise recovering and reselling components, first for internal fleet use and then to external buyers. Refurbished parts are increasingly available, supported by service exchange agreements, though uptake varies across the market. Remaining barriers include inconsistent standards, quality variability, and limited traceability. Interviewees also highlighted that the UK supply chain for wind turbine materials shows varying levels of maturity. Steel recovery is well established, with towers and monopiles largely recyclable, though much of the material is currently exported for processing before returning as manufactured products. Concrete foundations are commonly partially removed and recycled locally, by removing steel rebar and crushing the remaining material for use as aggregate. One interviewee highlighted there may be some potential for foundation reuse in site-specific circumstances. Blades remain the most challenging component, with limited UK recycling options and long-term solutions still under research, making near-term disposal reliant on mechanical recycling or, in some cases, incineration with energy recovery.

For the quantitative modelling, when considering the totals until 2070, for both onshore and offshore wind, the shorter lifetime was estimated to have the highest reuse potential (onshore 0.9 Mt, offshore 1.0 Mt), followed by BAU (onshore 0.8 Mt, offshore 0.6 Mt) and then longer lifetime (onshore 0.5 Mt, offshore 0.5 Mt). From the total reuse in each scenario, steel and iron (e.g., gearbox and generator) is approximately 87% for offshore wind, and 90% for onshore. The remaining mass for onshore (13%) and offshore (10%) is from blades (composite mass). However, constant reuse ratios were applied, and therefore more research is required in the future to further explore the reuse potential for turbines and components of each of the different lifetime scenarios. This is highlighted by the reuse ratio sensitivity analysis, which showed the difference between the longer and shorter lifetime total reuse reduced by approximately 14% (onshore) and 19.2% (offshore) as reuse ratios were varied from - 10% up to + 20%. As the reuse ratios were increased by + 20%, up to 0.7 Mt of additional materials were estimated to become available for onshore wind, and 1.1 Mt for offshore, further demonstrating the large impact a variation in reuse can have. Given that UK companies have been active as both buyers and sellers on the second-hand market, and that repair and refurbishment services are also offered in the UK, a detailed quantification of the reuse potential will be important, as this could become a crucial growth area for the UK.

The remainder that is not handled on the second-hand market, either enters a material recovery process or is not recovered. For onshore material recovery, the longer lifetime has the highest total mass (7.9 Mt), followed by BAU (7.6 Mt) and then shorter lifetime (7.3 Mt). Across all onshore scenarios, concrete contributes approximately 65.5% of recovered material, followed by 32.7% steel and iron, and 1.8% composites. Similarly for offshore material recovery, the longer lifetime also has the highest mass (10.7 Mt), followed by BAU (10.5 Mt) and then shorter lifetime (10.0 Mt). Across all offshore scenarios, steel and iron contributes approximately 97% of recovered material, followed by 2.8% composites, and 0.2% concrete.

The base scenario assumes a steel and iron recovery of 95%, however, currently most of the material recovery is done outside of the UK. Consequently, when varying the steel and iron recovery rates from 95% to 5%, up to 2.6 Mt (onshore) and 9.8 Mt (offshore) of recovered material is estimated to be recovered outside of the UK. For composite material recovery, a base-case recovery rate of 50% is assumed. However, as highlighted in the research review, achieving this rate will depend on the future scaling of the recycling infrastructure. Composite material recovery increases by up to 0.2 Mt for onshore wind BAU and 0.3 Mt for offshore wind BAU as recovery rates are varied from 50% to 100%. For concrete material recovery of onshore wind foundations, a base-case rate of 50% is assumed. For the BAU scenario an additional 5 Mt of concrete was estimated to be recovered as recovery rates increased from 50% to 100%. This highlights the importance of increasing the capacity to recover each of the materials in the UK and capture the available decommissioned material.

For both onshore and offshore wind, material recovery ratios remain constant across all lifetime scenarios, as these do not vary based on turbine age. However, for future analysis aimed at informing industry policies, it may be valuable to integrate scenario-specific variations in recovery rates, to account for the different timings of material flows. For instance, if material recycling infrastructure (e.g. for composites) still needs to be scaled in the UK, the BAU and longer lifetime scenario provide more time for the establishment of the infrastructure.

4.1.5 RQ 2b: What is the best use of recovered materials and components?

The literature review examined the quantitative economic, technical, social and environmental aspects of wind turbine material recovery under various circular economy pathways. Most studies focus on recycling, with limited coverage of reuse, refurbishment or repair. There was limited data on recovery and recycling rates for materials. There was also a lack of material-specific data on the value of recovered materials. Environmental impacts of blade treatments are better understood, with landfilling identified as the least favourable option. Mechanical recycling was considered the most energy-efficient, while methods like pyrolysis and solvolysis demand higher energy inputs – however, the resulting product quality and market demand must also be considered. The literature review identified that more empirical data is needed to refine the understanding of the economic, technical, and environmental implications of circular economy solutions for wind turbines.

Throughout the stakeholder interviews, asset owners and decommissioning companies described their sales process and hierarchy, with a strong preference for the sale of whole assets where possible. However, it was noted that the ability to sell whole assets is highly dependent on the model and condition of the turbine. Similarly to the whole turbine case, the opportunities for component resale is linked with the turbine model type and condition, with some of the less in demand models seeing as little as 5% resale of components by turbine mass, with the remainder sent for material recovery.

The stated preferred approach to material value adopted by the interviewed stakeholders aligns with the waste hierarchy. Life extension is already being seen for UK onshore wind assets, with similar expectations for offshore wind. When a turbine is decommissioned, the

process described for the resale of wind assets starts by investigating the opportunity for a whole asset sale. Where sale of the whole turbine isn't possible, companies will begin exploring sales for the components within the turbine. For turbine models that are highly in demand, components may be stored until a sale can be secured. Any remaining material following this process will then be sent for material recovery, often where the turbine is not desirable due to obsolescence or damage. Stakeholders also highlighted that achieving this preferred hierarchy in practice is constrained by several systemic challenges. Limited domestic and economically viable capacity for storage, refurbishment, and component reconditioning can restrict the ability to retain assets within higher-value pathways, particularly when decommissioning volumes increase. This is compounded by a lack of standardised guidance and established protocols for assessing component condition, resale potential, and safe disassembly practices, which can create uncertainty for operators and slow decision-making. Early engagement when consulting on decommissioning projects was highlighted as critical to being able to maintain the assets at their highest values. With knowledge on the correct handling of components like gearboxes noted as being particularly important such as not to damage the assets.

The emissions modelling suggests that increasing the reuse fraction of steel and iron (e.g., associated to reusing whole turbines, generators, or gearboxes) and composites (i.e. reusing blades) reduces the total emissions per energy generation for all scenarios for both onshore and offshore. As the reuse fraction is increased by 20%, the total emissions per energy generation decreased by up to 2.29 and 1.31 tonnes CO₂e per GWh for onshore and offshore wind, respectively. Steel and iron material recovery also had a significant estimated impact on reduction of total emissions per energy generation. As the recovery ratio increases from 5% to 75%, the net emissions impact decreases for both onshore (up to 2.15 t CO₂e/GWh) and offshore wind (up to 4.24 t CO₂e/GWh). To maximise emissions reductions, increased component reuse and steel and iron material recovery should be considered along with life extension.

The economic modelling suggests that refurbishment of wind components generally delivers greater economic benefits than material recovery alone, primarily due to its higher labour intensity and the retention of embedded component value. Across the scenarios assessed, refurbishment consistently generated higher employment impacts, supporting an estimated 14,000–26,000 jobs compared with approximately 10,000–12,000 jobs associated with material recovery activities. In contrast, material recovery can potentially generate higher overall GVA, estimated at £890–£1,020 million, if economic activity takes place within the UK, while refurbishment contributed approximately £300–£560 million. However, recognising this GVA is contingent on domestic processing capacity and retention of material value chains within the UK. In practice, a significant proportion of recovered materials is exported or processed through fragmented international supply chains, which limits the extent to which value is captured domestically. As a result, material recovery is less consistently realised as a UK-based economic activity compared to refurbishment, where labour-intensive processes and shorter, more localised supply chains more reliably translate into domestic employment creation.

It also highlights the significant influence of refurbishment assumptions on economic outcomes. Sensitivity analysis showed that relatively small increases in refurbishment rates can substantially increase both employment and GVA impacts. For example, a 5% increase in refurbishment rates was associated with around a 50% increase in economic impacts across the assessed scenarios. In several cases, scenarios with higher refurbishment assumptions under BAU or extended lifetime conditions produced impacts comparable to those observed under shorter lifetime scenarios with lower refurbishment rates. This underlines the importance of refurbishment in determining the overall economic value captured from end-of-life wind assets.

Overall, the findings suggest that prioritising refurbishment and second-life applications, where technically and commercially feasible, offers the greatest opportunity to maximise economic value retention and employment within the UK. However, material recovery remains an essential component of the end-of-life pathway, particularly for large structural elements such as towers and foundations, which have limited reuse potential beyond whole-turbine applications. Consequently, strengthening domestic recycling and material recovery capacity, and therefore by extension domestic manufacturing capacity, especially for steel and concrete, will remain critical to retaining economic value within the UK where refurbishment is not viable. Additionally, locally used second-life components or turbines can be fed into recovery processes after their use phase, if not entering a third lifecycle. When establishing the respective industries, attention must therefore be paid to the temporal and spatial shifts in resource flows, which highlights the importance of establishing a traceability system.

4.1.6 RQ 3a – 3c: Identify economic impacts of repair and recovery activities for wind assets

4.1.6.1 Literature review and stakeholder interviews

The literature review and stakeholder interviews revealed a high variation in the findings and thereby negates consensus. Onshore and offshore wind may have fundamentally different business cases for lifetime extension, due to the 2-3 times higher O&M costs in the marine environment. Preventative maintenance methods have high potential to reduce costs, with early repairs reported to save 2-12.5% of costs and condition-based maintenance a further 8% saving in O&M costs. A secondary market for refurbished parts has started to create new revenue streams. Blade recycling is constrained by high costs while REE recycling face volatile prices and technical challenges. Identified economic challenges included the perceived limited capacity relative to the volume of projects, a higher barrier to entry for working on offshore components, and logistical issues related to material movement. Early pipeline certainty, targeted investment, and maintaining high-quality, specialised services are seen as essential to addressing these risks and sustaining domestic supply chain development.

For repair and recovery activities jobs impacts, there is high potential but uncertainty about job creation was also identified, with limited evidence sources to draw upon. Repair, recovery and recycling could create substantial job opportunities, with estimates of up to 20,000 jobs in the UK by 2030. Interviews also provided new estimates for labour requirements and costs associated with MCE operations, and decommissioning, which informed the quantitative

modelling. Policy incentives are critical for enabling blades and magnets solutions with a difficult economic case.

Many larger companies, such as asset owners, have relatively small, or in some cases, no teams specifically dedicated to decommissioning or life extension. Similarly, for material recovery companies, it was noted that only relatively small quantities of materials are currently being sourced from the wind industry, therefore dedicated teams may be as small as one or two personnel who draw heavily on support from the wider business. The landscape described for refurbishment companies, including some European workshops, was dominated by SME's ranging in size from micro SME's of less than five people, up to medium sized companies of 80 people.

The literature review and stakeholder interviews also suggested there is high potential for the UK economy from repair and recovery activities, but the evidence base is too unreliable for a consensus result. There remains a significant knowledge gap on the potential GVA by repairing and recovering material from existing wind assets.

4.1.6.2 Economic impacts of repair, recovery and O&M activities

When only considering the repair and recovery activities for onshore wind, the shorter lifetime scenario delivers the highest employment impact (42,000 job-years), followed closely by the BAU (41,000 job-years), and longer lifetime scenario (37,000 job-years). The GVA is broadly comparable across all scenarios. Similarly for offshore wind, considering repair and recovery activities in isolation, the shorter lifetime scenario delivers the highest level of employment (79,500 job-years). In this case, the difference between the shorter and longer lifetime scenarios is approximately 10,500 job-years, indicating a relatively clear advantage for the shorter lifetime case within this limited scope of activities.

For both onshore and offshore wind employment, turbine and component refurbishment is the metric with the greatest variation between scenarios, driven by higher reuse assumptions. As mentioned in Section 4.1.4, more research is required in the future to further explore the reuse potential for turbines and components of each of the different lifetime scenarios.

However, when O&M is also considered, the longer lifetime scenario becomes the most economically beneficial overall for both onshore (504,000 jobs-years and £13,700 million) and offshore wind (1,330,000 jobs-years and £19,100 million). The 10-year life extension from the shorter lifetime scenario increases economic benefits by approximately 115,000 job-years and GVA by £2,900 million for onshore wind, and by approximately 394,000 job-years and GVA by £4,300 million for offshore wind. This reflects the sustained employment and value creation associated with continued asset operation, which outweighs the increased activity associated with shorter lifetimes.

This highlights the importance of taking a whole-system, lifecycle perspective when assessing economic outcomes. Focusing on a narrow subset of activities can lead to different conclusions than those reached when O&M and longer-term operational benefits are included, underscoring the need for comprehensive analysis in informing investment and policy

decisions. While repair and recovery phases are more concentrated under shorter lifetimes, O&M activity accumulates over time and becomes increasingly significant in shaping total employment outcomes. As a result, lifecycle duration has a material influence on both the scale and distribution of economic benefits.

Additionally, the relatively low assumed UK content in key offshore activities, particularly MCE and decommissioning, represents a missed opportunity for domestic economic capture. A substantial proportion of high value offshore work is instead delivered through international vessels and supply chains. This limits the extent to which these lifecycle phases translate into UK employment and GVA, despite their significance in the overall offshore wind value chain. Additional activities associated with turbine and component reinstallation, as well as repowering, could generate significant additional economic impacts that are not captured within the current assessment and could be considered in future work.

4.1.6.3 Economic impact sensitivity analysis

A sensitivity analysis was used to understand the impact of individual activity types across the value chain. For onshore MCE, as modelling assumptions were varied, longer lifetime remained the most beneficial scenario. For employment, an increase of 20% in the modelling assumptions, created up to 1,400 more job years. While for GVA, an increase of up to £970 million was estimated as assumptions increased by 50%. However, this variation was seen across all scenarios and didn't impact the ranking of lifetime extension benefits.

Offshore MCE activities are assumed to take place largely outside the UK economy, reflecting the structure of the existing supply chain and the specialised nature of the assets and services required. In particular, critical infrastructure, such as jack-up vessels, are predominantly owned and operated by non-UK companies, with limited domestic availability. As a result, much of the expenditure associated with component fabrication, vessel charter, heavy-lift operations, and associated logistics is captured outside the UK economy. It is recommended that further work is carried out to refine and improve the estimates associated with offshore MCE.

The economic results are highly sensitive to the assumed refurbishment rate. Sensitivity analysis showed that relatively small changes in the proportion of components directed towards refurbishment can materially alter both employment and GVA outcomes. Across the onshore scenarios assessed, refurbishment was estimated to support approximately 14,000–26,000 jobs, compared with around 10,000–12,000 jobs associated with material recovery activities. Whilst the GVA values were £300–£560 million and £890–£1,020 million respectively. This suggests that, where technically feasible, prioritising refurbishment and second-life applications could maximise the economic value retained from end-of-life wind assets.

A significant area of uncertainty relates to the proportion of activity that will be retained within the UK supply chain, particularly for steel and composite material recovery. As material recovery varies from the base case of 95% to 5% for steel and iron, UK employment decreases by up to 5,100 job-years for onshore wind and approximately 19,000 jobs-years for offshore wind. For GVA, the decrease for onshore and offshore wind is £580 million and £2,020 million, respectively. For composites, as material recovery increased from the base

case of 50% to 100%, UK employment increases by up to 1,400 job-years for onshore wind and approximately 2,900 jobs-years for offshore wind. For GVA, the increase for onshore and offshore wind is £95 million and £180 million, respectively. This highlights the economic benefit of domestic material recovery, especially from offshore wind steel and iron. Concrete recovery was assumed to be fully localised within the UK due to logistical challenges associated with long-distance transport. While concrete recovery is already an established domestic activity, additional scale-up in processing and handling capacity may be required in the future to manage increasing volumes of removed concrete foundations during decommissioning. The extent of this required capacity will depend on whether full or partial foundation removal is undertaken, as well as the level of demand for recovered aggregate across other construction and infrastructure sectors.

For the total decommissioning activity, the primary point of variation is the timing of the economic impacts, with shorter lifetime scenarios bringing forward decommissioning activity, while longer lifetime scenarios defer it. This shift may have implications for the distribution of jobs and GVA over time, as well as for supply chain readiness and workforce planning, but does not materially affect the overall scale of decommissioning-related economic activity. This indicates that the key consideration is not the overall level of economic benefit generated, but how it is distributed over time. A more gradual trajectory may better align with current market conditions and delivery constraints, supporting smoother capacity building and reducing the risk of bottlenecks, while a more front-loaded profile would require earlier and more coordinated interventions to ensure readiness across the supply chain.

For offshore wind decommissioning, increasing the share domestic decommissioning activities from the baseline assumption of 18% to 100%, increases GVA by approximately £5,400 million. This highlights a significant potential opportunity for the UK supply chain that is currently not being fully realised, particularly in areas such as specialised vessel provision and high-value engineering services. Increasing domestic capability and participation in these segments could materially enhance the proportion of value captured within the UK economy.

4.1.7 Future work

During the course of the study, a number of key areas for future work and further investigation were identified. While the findings of this research provide valuable insight into the opportunity for repair and recovery of components and materials from the wind sector, they also highlight several limitations and opportunities for development that could be explored in subsequent studies. Future work may focus on expanding the scope of the research, refining the methodologies employed, and incorporating additional data sources or analytical techniques to improve the depth, reliability, and applicability of the results. Furthermore, advancements in related technologies and emerging industry practices present opportunities to build upon the foundations established in this study, enabling a more comprehensive understanding of wind turbine life extension and supporting continued innovation within the field.

4.1.7.1 Future analysis

The findings of this study highlight several important areas for future research and methodological refinement. In particular, the assumed timing of decommissioning was shown to have a strong influence on projected material flows. Consequently, individual project-level decision-making within the wind sector can significantly affect overall material flow projections, particularly for offshore wind. Future work should therefore consider more detailed project-level assessments that incorporate factors such as permitting and lease conditions, CfDs, PPAs, turbine technologies, developer strategies, and grid connection requirements. Such an approach would provide a more representative understanding of how operational and commercial decisions influence long-term material flows. Furthermore, regional differences across the UK should be considered in order to capture potential variations in infrastructure, policy, and market conditions influencing material recovery and reuse pathways. In this context, aligning future energy system planning and project-specific considerations, such as repowering potential and anticipated decommissioning timelines, with broader industry development is recommended.

Additionally, the material flow modelling undertaken in this study aggregated pathways into three broad categories: (i) second-life applications of turbines or components, (ii) material recovery pathways (e.g. repurposing, mechanical recycling, etc.), and (iii) pathways without material recovery (e.g. landfilling, incineration with energy recovery). This simplified framework enabled the study to address the current lack of comprehensive empirical data in the UK while still representing an assumed cascading flow structure for materials and components. However, as additional empirical evidence becomes available, future research should refine this modelling approach by introducing time-dependent pathway shares that better reflect evolving industry practices and technological developments. A clear distinction was identified between the reuse of complete turbines and the reuse of individual spare parts, with each representing separate demand markets and requiring different approaches for managing material flows. Future research should therefore strengthen this distinction within modelling frameworks and seek to collect more comprehensive empirical data on the resale and reuse of smaller components and drivetrain parts, such as brake callipers, for which little systematic information currently exists. In addition, future work could refine the classification of material recovery further by distinguishing between high, mid, and low-value recycling as well as between open (e.g. blade-to-new product) or closed-loop recycling (e.g. monopile-to-monopile or blade-to-blade).

Future analyses should also consider the role of component replacements associated with lifetime extension strategies, including converter upgrades and other retrofit measures that may alter future material demands and waste generation profiles. In addition, future work should more explicitly link replacement-rate modelling with the estimation of remaining technical lifetime at both turbine and component level. This would support the development of more effective operation, maintenance, and repair strategies, while improving the robustness and accuracy of long-term material flow modelling. Differentiated failure-rate models that explicitly account for turbine design characteristics, maintenance strategies, component ageing, and varying environmental conditions over time could be developed. Such research

would improve understanding of how replacement rates evolve with turbine age across different turbine technologies, as well as how predictive maintenance strategies may contribute to reducing failure rates, lowering operational costs, and extending operational lifetimes.

4.1.7.2 Traceability system and empirical data collection

Maintaining accurate records of decommissioned wind assets currently relies on a continuous updating process that draws upon multiple information sources, including cross-checking against available databases, press releases, company websites, and social media posts to identify decommissioned sites. To improve the accuracy, consistency, and transparency of such datasets, future work should consider the introduction of mandatory reporting requirements for asset owners to provide up-to-date project status information to the Renewable Energy Planning Database (REPD), similar to the reporting obligations implemented by the Federal Network Agency in Germany. In addition to reporting requirements on turbine decommissioning status, the establishment of a broader tracking and reporting system is recommended to track turbines, components, and parts beyond their first use phase, including tracing circular flows across borders and sectors. Improved visibility of asset movements and secondary use pathways would strengthen the evidence base for future planning and support more effective coordination across the supply chain, including for decommissioning contractors, refurbishment companies, and O&M service providers.

The study also identified substantial variability in the data reported across different turbine designs, O&M strategies, environmental conditions, and turbine ages. Where consistent empirical datasets were limited, minimum, maximum, and average values were employed to account for uncertainty within the analysis. This was particularly evident for economic data, where significant variation exists in reported costs associated with operation and maintenance activities, component replacement, refurbishment, transport, recycling, and decommissioning. In many cases, economic information remains commercially sensitive, highly project-specific, or insufficiently reported within the literature, resulting in considerable uncertainty regarding the financial viability of different end-of-life and lifetime extension pathways. Future work should therefore focus on improving the availability, transparency, and consistency of empirical economic datasets, including more detailed reporting of O&M costs, replacement expenditures, refurbishment costs, and revenues associated with reuse and material recovery pathways.

4.1.7.3 Transferability to other sectors

This study was designed to derive an understanding of the wind sector and the existing wind assets in the UK. The methodologies of the literature review, expert interviews, material flow modelling as well as the economic and emissions impact modelling were carried out in a structured way and were transparently documented. Moreover, wherever feasible, industry-neutral frameworks were applied. For example, the industry-neutral 9R-ladder reference framework 9R-ladder reference framework, outlining the cascade of circular economy strategies, was applied to enable transferability of the analysis process to support assessments in other industries.

Thereby enabling the transferability of the study's methodology to other sectors such as to the photovoltaic and batteries sectors. In addition, the findings of this study can be used for comparison to market dynamics in other sectors with similar characteristics, i.e. large, multi-component products with a long lifetime, and consequently support the identification of cross-sector actions and behavioural trends. Cross-sector actions could, for instance, be the establishment of a traceability system or the development of a domestic recycling strategy. The latter involving the aggregation of estimated material recovery streams from different sectors and linking them to potential demanding sectors. A further example is to better understand the potential transferability of skilled labour and logistical capacities across sectors in order to further support the scaling of domestic activities such as repair, refurbishment and decommissioning.

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Appendix A: Literature review methodology

A.1 Search and screen methods

Literature searches were carried out on Scopus and Web of Science (5. November 2025), focusing on search terms in titles, abstracts and key words, at all times and in all languages (Table 41). All search results were entered into Excel, keeping track of which entries were identified for which topics by adding an “x” in the respective topic column in the database. Search results were then sorted by Digital Object Identifier (DOI) or, if there was no DOI, by title, to identify duplicates and merge them into one row. This resulted in a database with 4,762 scientific publications.

Publications were longlisted before the screening of titles and abstracts. Only publications in English that were relatively recent from 2015 and later were selected. This selection was made to reflect current thinking in the subject area and to capture the most up-to-date publications. Moreover, the recent selection helped to limit the number of results in order to maintain a feasible scope in the short timeframe we had available to conduct the project. After this step, there were 3,821 publications remaining.

Further longlisting steps were taken based on review priorities, selecting all publications for topic categories for which a systematic review was planned (Table 41). For topic categories for which a narrative review was planned, publications were prioritised for screening that either presented reviews, mentioned the key word “empirical” in titles or abstracts, and/or were highly cited. Screening limits for being classed as “highly cited” were set pragmatically based on volume of literature within the topic category; for RQ 1a – where literature was slightly less prevalent – everything cited >10 per annum was selected, and for RQ 2a, 2b and 3a – where literature was more prevalent – everything >15 per annum was selected.

Prioritised publications were then screened by reading titles and abstracts to check for likely relevance against the topic(s) under which the publication was identified based on topic descriptions (Table 41). Publications were marked by changing the “x”, which indicated that it had appeared in the search results for specific topics as explained above, into an N = not relevant for review, M = maybe relevant, Y = yes relevant for full review. In case of an “N”, comments were added with reasons for exclusion. In case of an “M” or “Y”, a brief indication was added to describe what the publication was about to aid full review later. Moreover, some publications were marked as “high priority”, to be prioritised for full review. Topic category 2x was fully screened as an example, before a team of multiple individuals proceeded with the screening. Regular meetings were held throughout the screening process to further ensure consistency of the screening approach within the team.

Table 41: Scientific literature search queries and results per topic area.

Topic	Description	Search queries	Unscreened titles	>2015, English	Review approach
1a	Potential for repair and maintenance to extend existing wind turbine lifetimes	("wind turbine" or "wind turbines") AND (repair* OR maint*) AND ("lifetime extension" OR durab*)	186	154	Narrative
1b	Net-impact of lifetime extension on material demand, compared to material recovery and manufacturing into new wind assets for UK market and business-as-usual	wind AND "lifetime extension" AND material*	32	30	Systematic
1c	Net-impact of lifetime extension on emissions	wind AND "lifetime extension" AND (emission* OR carbon OR "life cycle assessment" OR LCA)	109	89	Systematic
2a	Potential component reuse and material recovery from existing wind assets, for UK, or as proportions for current capacity stocks in other countries	(wind asset* OR "wind turbine*") AND (reus* OR repair* OR refurb* OR remanuf* OR recover* OR recycl*)	4,514	3,614	Narrative

Topic	Description	Search queries	Unscreened titles	>2015, English	Review approach
2b	Quantifications and comparative assessments of economic, technical, social or environmental values of materials and components in wind under diverse scenarios	(wind asset* OR "wind turbine*") AND (reus* OR repair* OR refurb* OR remanuf* OR recover* OR recycl*) AND (social* OR environmental* OR economic* OR techn*) AND (value* OR impact*)	798	687	Narrative
2x	Business models in the UK and/or with potential to transfer to the UK market	wind AND "business model" AND (reus* OR repair* OR refurb* OR remanuf* OR recover* OR recycl*) AND (social* OR environmental* OR economic* OR techn*) AND (value* OR impact*)	16	16	Systematic
3a	Economic impacts of repair and recovery activities	("wind asset*" OR "wind turbine*") AND (repair* OR recover* OR recycl*) AND (economic* OR business*)	598	505	Narrative
3b	Impacts on jobs of repair and recovery activities	("wind asset*" OR "wind turbine*") AND (repair* OR recover* OR recycl*) AND (job* OR employment)	16	14	Systematic

Topic	Description	Search queries	Unscreened titles	>2015, English	Review approach
3c	GVA potential of repair and recovery activities	("wind asset*" OR "wind turbine*") AND (repair* OR recover* OR recycl*) AND (GVA OR "gross value added")	20	18	Systematic

A total of 2,075 publications were screened, of which varying proportions per topic area were deselected for the full review. Publications with a low citation rate of less than 2 per annum were not included, removing 1,037 publications published up to 2023 (publications from 2024-2026 were not subjected to this rule). Other reasons for deselecting were due to publications not being about wind energy, purely theoretical / about theoretical designs, about niche topics, or irrelevant to topics, e.g. aero-hydrodynamic analysis, modelling of aerodynamics, condition monitoring and maintenance strategies, hybrid energy generation site analysis, general REE recycling, small turbines. Screening efforts have been pragmatic, being stricter for topics with a high volume of search results and where possible being more forgiving with modestly populated topics, impacting on rejection rates per topic (Table 42).

Table 42: Number of scientific publications screened per topic area with numbers of outputs progressing to the review stage (marked Y=yes or M=maybe) or being deselected (N=no) with the overall rejection rate in the topic area.

RQ	Total screened for each RQ	For full review			Rejection rate (%)
		Y	M	N	
1a	72	19	8	45	63
1b	30	11	9	10	33
1c	105	33	34	38	36
2a	1936	97	116	1723	89
2b	691	65	133	493	71
2x	16	5	5	6	38
3a	391	42	38	311	80

RQ	Total screened for each RQ	For full review			Rejection rate (%)
		Y	M	N	
3b	14	3	1	10	71
3c	18	5	5	8	44

A.2 Review methods

A total of 397 scientific publications were shortlisted for full review, and 64 grey literature publications were added based on project partners existing libraries and online searches for the latest additions. This resulted in the literature review database with 461 publications.

The total body of literature for review covered the topics from diverse angles based on type of wind (12% onshore, 21% offshore and 3% floating wind), component focus (dominated by blades 49% and foundations 24%) and material focus (dominated by composites 33% and cement 21%). To ensure efficient delivery of the review and avoid likely duplication of efforts, a further prioritisation of publications for full review was applied to bring underrepresented categories to the fore and to ensure balanced coverage of onshore / offshore wind and of all components and materials.

Together with priorities allocated at the screening stage, this led to prioritisation of publications for full review:

- Priority 4: when marked as high priority in screening stage
- Priority 3: everything <10% of total shortlisted publications list and publications falling into systematic review category, if not already marked as priority 4
- Priority 2: everything not (de)prioritised
- Priority 1: publications marked as likely low value-added in screening stage

Representation of publications focused on offshore/onshore were harmonised in the reviewed articles (Table 43), raising representation of onshore wind from 12% in the total review database to 32% in the reviewed literature and offshore wind from 21% to 33% by reducing publications without a particular wind focus from 73% to 47%. Similar efforts were made for components (

Table 44) and materials (Table 45) reducing the overrepresentation of blades and composites to increase coverage of other parts and materials.

Table 43: Wind types in the reviewed literature and the literature review selection list.

Topics	Reviewed literature		Literature review selection list	
	Number	Percentage (%)	Number	Percentage (%)
Onshore	38	32	55	12
Offshore	40	33	96	21
Floating	8	7	14	3
None	56	47	334	73

Table 44: Components in the reviewed literature and the literature review selection list.

Topics	Reviewed literature		Literature review selection list	
	Number	Percentage (%)	Number	Percentage (%)
Foundation	34	28%	112	24.3%
Tower	21	18%	30	6.5%
Nacelle	16	13%	17	3.7%
Blade	43	36%	225	48.8%
Bearing	10	8%	20	4.3%
Magnet	16	13%	37	8.0%
Generator	25	21%	42	9.1%
Cable	12	10%	22	4.8%
None	33	28%	138	29.9%

Table 45: Materials in the reviewed literature and the literature review selection list.

Topics	Reviewed literature		Literature review selection list	
	Number	Percentage (%)	Number	Percentage (%)
Steel	27	23%	47	10.2%
Cement	17	14%	96	20.8%
Concrete	17	14%	44	9.5%
Composite	28	23%	152	33.0%
Copper	17	14%	22	4.8%
Aluminium	11	9%	13	2.8%
Neodymium	16	13%	29	6.3%
Critical material	12	10%	17	3.7%
REE	21	18%	45	9.8%
None	53	44%	200	43.4%

Publications were reviewed using a systematic standardised framework in Excel for consistency in the review approach and organisation of review results by multiple team members. The standardised review format included columns with copies of publication details, copies of screening comments to help focus and accelerate publication reviews, and results from automated searches for terms to group results by onshore/offshore, components and materials. Each publication was subjected to review, completing the following information:

- Reviewer summaries of 30-50 words to give context for the topic specific notes.
- Assessment of relevance of the publication scored 0-5, with 0 not displaying any relevance upon starting detailed review, and 1-5 being not relevant to highly relevant for the purpose of this project.
- Insights from publications on the topics of interest – initially marked as Y / M / N copied from the screening results, to focus review efforts on the relevant topics for each publication – adding detailed notes with sufficient context to enable interpretation when reporting the results.

- Empirical data sources that were used, generated by the study itself or referenced in the publication from secondary sources, to possibly feed into Phase 3 modelling and quantitative assessments.
- Checks of the automated categories on wind type, components and materials.

Publications were sourced online using the DOI, publication title, authors(s) and year through Google Scholar. Most publications were available freely. Some had to be sourced directly from the authors, e.g. through ResearchGate or by contacting them directly for a copy. A small proportion of publications could not be accessed.

Publications were allocated to reviewers. Reviews focused on high priority publications in the first instance, working down through the priority list. A small number of publications was reviewed by two reviewers, to allow for consistency checks for the application of the review approach by multiple team members. These checks rendered similar review findings, which confirmed the consistency within the methods.

Not every publication turned out to be equally useful for the purposes of this project, with scores for relevance slightly skewed towards the lower end. Nevertheless, 34% of publications scored a three or higher i.e. as being (extremely) relevant (Figure 67).

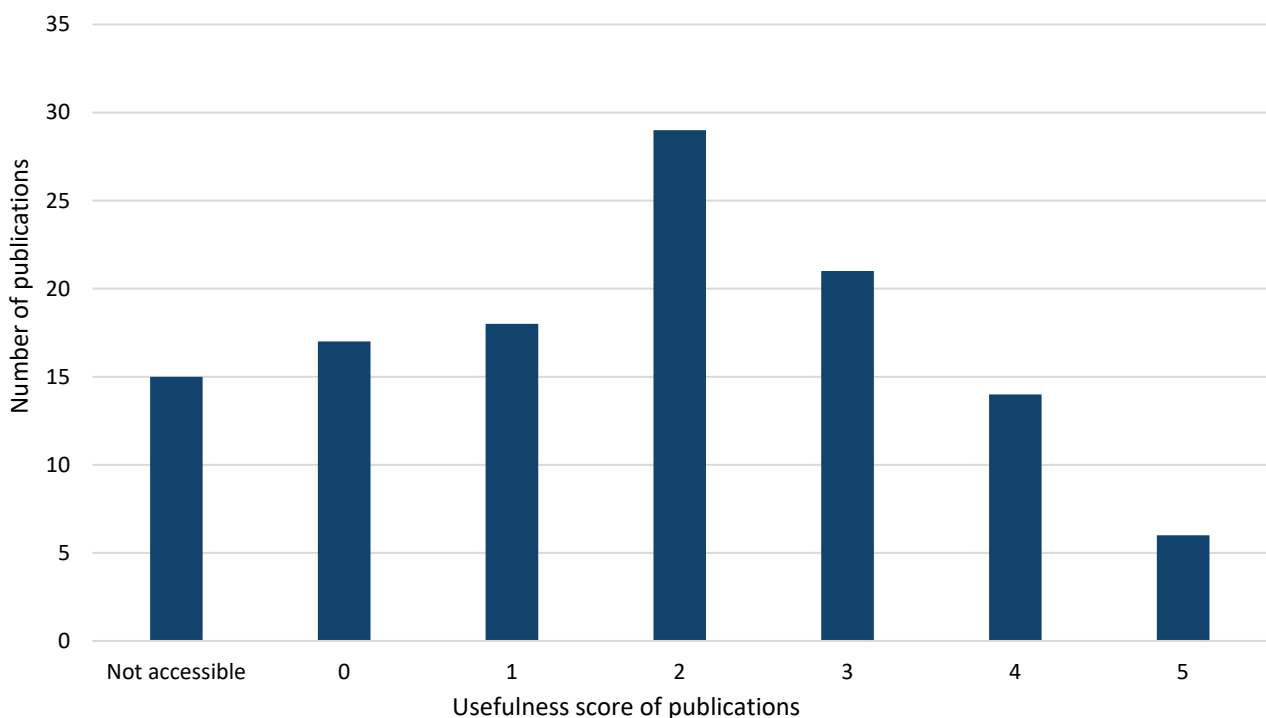


Figure 67: Number of publications (y-axis) per usefulness score (x-axis) of publications, where not accessible refers to publications not reviewed due to inaccessibility and scores 0=not useful at all and 5=extremely useful for the purpose of this project.

Appendix B: Material flow modelling

B.1 Material flow methodology

B.1.1 Major replacement rates

Table 46: Overview of major replacement rates from existing research.

Studies	Technology	Replacement rates
Walgern et al. (2016) – PRE PRINT	Offshore	<p>4.3 failures per offshore wind turbine and year</p> <p>1.088 failures per MW per year for offshore wind turbines</p> <p>Highest failure rates for the subsystems rotor system, control system, lifting gears and converter system.</p> <p>Major component replacements only provided for offshore and only in the unit of “per MW”. The choice of unit is criticized by one reviewer – so not used until we know that the paper is accepted</p> <p>No events recorded for the nacelle, tower, transition piece and foundation</p>
	Onshore	<ul style="list-style-type: none">• 3.3 failures per onshore wind turbine and year• 1.729 failures per MW per year for onshore wind turbines• Highest failure rates for the subsystems rotor system including the pitch system, control system, drive train system and converter system. However, do not state quantities on major replacements
Faulstich et al. (2011)	Onshore	<ul style="list-style-type: none">• 2.4 failures per onshore wind turbine and year• Highest failure rates for the electrical system (0.57) and control systems (0.43). Rotor blades at 0.11, rotor hub at 0.17, gearbox 0.1, generator 0.11 and drive train 0.05.• When only looking at major failures: 0.02 rotor blades, 0.06 rotor hub, 0.03 gearbox, 0.04 generator, 0.02 drive train

Studies	Technology	Replacement rates
Carrol et al. (2016)	Offshore (2-4 MW turbines)	<ul style="list-style-type: none"> 8.3 failures per offshore wind turbine and year. Figure includes 0.3 major component replacements, 1.1 major repairs, 6.2 minor repairs and 0.7 uncategorised data. Most major replacements for gearboxes, followed by generator 0.154 replacements per turbine and year for gearbox 0.001 replacements per turbine and year for blades 0.095 replacements per turbine and year for generator
Schreiber et al. (2019)	Onshore (3 MW turbines)	<ul style="list-style-type: none"> 0.95 replacements/20 years of gearbox (thus not for direct drive technology) 0.46 replacements/20 years of rotor Depending on generator design: 0.19 replacements/20 years of DFIG generator 0.35 replacements/20 years of DDSG generator 0.24 replacements/20 years of DDPMSG generator
Andersen et al. (2015)	Onshore	<ul style="list-style-type: none"> Gearbox, generator, and rotor blades are most replaced parts Replacement rates from a study from Germany and from the USA. Average values used by Tota-Maharaj et al. (2021). 3.1% replacements per turbine and year of gearbox (thus not for direct drive technology) 2.2% replacements per turbine and year of each blade 2.9% replacements per turbine and year of generator

Studies	Technology	Replacement rates
Shammugam et al. (2019)	Onshore & Offshore	<ul style="list-style-type: none"> Adapted from Carrol et al. (2016) and Carrol et al. (2017) Consider in MFA most frequent failures, i.e. of pitch, gearbox and yaw, and also include generator failures (due to REEs presence). See Tab 12 below. 0.059 replacements per turbine and year for multiple-stage gearbox and 0.042 for single-stage Depending on generator design different rates, varying from 0.007 (PMSG-HS), 0.008 (PMSG-GB), 0.009 (PMSG-DD) to 0.109 (DFIG, EESG-DD, SCIG) failures per turbine and year for generator Blades not included, but pitch and yaw system Provide major replacement, major repair and minor repair rates Do not differentiate between onshore and offshore, for pitch, yaw and gearbox, but indirectly for the generator as different rates for different generator designs are considered.
Godoy León et al. (2025)	Onshore & Offshore	<ul style="list-style-type: none"> Used data from Shammugam et al. (2019): For gearbox they take the average from multiple-stage and single-stage gearbox, i.e. 0.051, and other than that the same values. Assume 100% of material of the component to be replaces in the case of major replacements. Do not differentiate between onshore and offshore, for pitch, yaw and gearbox, but indirectly for the generator as different rates for different generator designs are considered.

Studies	Technology	Replacement rates
Dao et al. (2019)	Onshore & Offshore	<ul style="list-style-type: none"> • Values only provided as graph, not as table, and doesn't differentiate between repairs and replacements: • ~0.75 failures per offshore turbine p.a. for blades & hub, and ~0.15 for onshore • ~0.6 failures per offshore turbine p.a. for gearbox, and ~0.15 for onshore • ~1 failures per offshore turbine p.a. for generator, and ~0.2 for onshore • When individual subassembly data are combined, the offshore WT failure rate is roughly three times the weighted average onshore WT failure rate. According to Mishnaevsky et al. (2020), for blades & hub the failure rate per turbine per year is 4 times higher for offshore than for onshore wind turbines
Avanessova (2023)	Offshore (6MW+, most likely direct drive)	<ul style="list-style-type: none"> • Major component replacement of 0.04 per year (p.49) • Major replacement activities (p. 150): • Blade: 0.03 p.a. • Gearbox: 0.009 p.a. • Generator: 0.003 p.a.
Donnelly et al. (2024)	Offshore	<ul style="list-style-type: none"> • Major generator replacement rate p.a. per turbine: • 1.0% geared drive train system • 2.1% direct drive system • Major gearbox replacement rate p.a. per turbine: 2.2%
SPARTA report (2022)	Offshore	<ul style="list-style-type: none"> • Data on major repairs that are defined as repairs that require a jack up vessel, but it's not broken down further than that for repair/replace, nor is it broken down per component. Only the number of forced outages is presented per component.

B.1.2 Fleet data quality assessment

Quality assessment of fleet market data and data preparation

The following described the process and key findings of the quality assessment and data preparation of the fleet market data and associated material quantities.

Fleet market data

To assess whether the datasets represent the entire market history, they were cross-checked with publicly available sources (e.g. REPD). Data gaps and outliers were reviewed with a particular focus on data quality of the project status, installation year, decommissioning year, installed capacity, turbine model, manufacturer, and rotor diameter.

RUK records a higher number of decommissioned wind assets than REPD; however, this relies on a continuous updating process that draws on multiple sources to identify decommissioned sites. The status of several onshore wind turbines was cross-checked against available databases, press releases, company websites, and social media, revealing some discrepancies compared to RUK. Despite these variations, RUK remains the most comprehensive data source currently available. However, to improve data accuracy and consistency going forward, it is recommended that asset owners be required to report the latest project status to REPD, similar to the reporting obligations enforced by the Federal Network Agency in Germany.

A further limitation of the RUK dataset is the presence of data gaps for the attributes 'wind turbine manufacturer' and 'wind turbine model/type' affecting 12.1% of the wind farms captured, corresponding to missing data for 4.8% of total number of onshore turbines. In addition, turbine model information is sometimes recorded at a general rather than specific level. Despite these limitations, the attributes are retained in the dataset, as they provide valuable information for the potential of the second-hand market (see chapter 3.1.2.2.2.2).

Validation for offshore wind was more straightforward due to a smaller number of wind farms. The project status in the ORE Catapult dataset was compared to the RUK database, and discrepancies cross-checked with alternative sources. Following this work, some installation dates and expected installation dates were corrected. Operational lifetime calculations are based on the date of full farm commissioning, as turbine-level commissioning dates are not available. It should be noted, however, that in projects such as Dogger Bank A, some turbines are already operational despite the project status being under construction.

It is assumed that all offshore wind farms consist of new turbines, and that onshore installations are also predominantly new. However, the exact share of second-hand turbines in the onshore fleet is unknown. For the purposes of the material flow modelling, it is therefore assumed that 100% of installed turbines are new.

Material intensity data

To assign material intensity data to the onshore fleet, the following approach was taken for the materials under consideration in this study. The mass of blade composites is added with a regression function based on blade length per turbine (Abrahamsen et al., 2023). Where data gaps existed, values were approximated based on installed capacity according to Tota-Maharaj et al. (2021). Steel, iron, and concrete masses were also estimated with regression functions from Tota-Maharaj et al. (2021), a UK-specific material flow study, covering turbines in the range of 5 kW-5MW.

For the offshore wind data, material intensity data was already included in the original dataset, with quantities provided for key components across different foundation types and appropriately scaled.

A review of the methodologies resulted in a minor change to the calculation for composite blades, as the initial approach led to a slight overestimation for smaller offshore turbines. The regression function by Abrahamsen et al. (2023) was applied for turbines up to 8.4 MW (corresponding to a fitted range up to 167 m rotor diameter), while the methodology used by ORE Catapult was used for larger turbines (≥ 8.8 MW).

It was also identified that the applied scaling functions could lead to a slight overestimation of the iron and steel masses for the smaller wind turbines and geared turbines in the offshore portfolio. This was not corrected as this would have exceeded the scope of the study. However, it should be noted that the steel and iron mass of the foundation accounts for a significant proportion of the total steel and iron mass. These were calculated separately for each foundation type, taking project-specific water depth into account. As a result, the impact of this overestimation is limited primarily to component replacement calculations. For the generator and gearbox, additional masses were available for various sizes and were therefore used to calculate the equivalent mass.

Within the current offshore fleet, only the Project 'Blyth Offshore Demonstrator phase 1' uses concrete foundations. As this was not included in the provided dataset, it was added using an assumption of 810 t/MW (ORE Catapult and Zero Waste Scotland, 2022). While small quantities of concrete may also be used for grouted connections between transition pieces and monopiles, these were excluded from the analysis. In the future, concrete is expected to become more important for installations in deepwater, for both floating and fixed-bottom offshore wind (ORE Catapult, 2024).

Finally, the dataset was filtered to align with the scope of the quantitative modelling (Section 3.1.1.1). Projects not yet under construction and not expected to be commissioned by 2027 were excluded.

B.1.3 Expected lifetime of wind turbine fleet

Onshore wind – BAU scenario

In the BAU scenario, a Weibull function is fitted to the ratios of decommissioned to installed capacity by installation year of the UK onshore fleet. The Weibull parameters $\lambda = 33$, $k = 12$

were derived. A detailed description of the methodology is provided in Abrahamsen et al. (2023). The fitted Weibull function suggests that the UK onshore wind fleet already exhibits characteristics of a lifetime extension scenario. According to the model, 50% of the fleet is expected to be decommissioned after approximately 32 years.

It should be noted that the Weibull fit is sensitive to data availability and should be updated as additional data points and a longer time series become available. In particular, early-year ratios are highly sensitive to a small number of projects, underlining the importance of interpreting the results in the context of broader market characteristics and the findings from the research review.

The results are consistent with observations across Europe, including the UK (Mc Govern et al., 2025). In addition, the current UK onshore market shares similarities with Denmark, where recent years have seen limited new onshore installations and relatively small average turbine sizes (Kramer, 2025). This provides a plausible explanation for the similar lifetime behaviour observed.

Stakeholder interviews indicate that lifetime extensions of 5–10 years are commonly considered. It is also expected that smaller operators, in particular, may prefer lifetime extension over repowering, especially where sites are not ideally suited for redevelopment. Furthermore, current market conditions are not seen as strong drivers for repowering (see section 2.6.4). Therefore, while the interviews are not fully representative of the entire UK market, they provide qualitative support for the trends reflected in the fitted Weibull distribution.

Onshore wind – shorter lifetime scenario

A shorter lifetime scenario is introduced to capture potential developments that may lead to earlier decommissioning compared to the BAU scenario. For example, second-life turbines may exhibit reduced operational lifetimes. In addition, as discussed in Section 2.1.1.1.4, recent and potential future changes in the policy environment may accelerate decommissioning and increase repowering activity. Some turbines are expected to exit the ROC scheme in 2027, which may reduce the economic viability of continued operation. At the same time, restrictions on new onshore wind installations in England have been lifted and the planning process for permitting repowering projects has been eased. However, not all sites are suitable for repowering due to constraints such as height restrictions or logistical limitations. As a point of reference, repowering currently accounts for approximately 30% of annual onshore wind installations in Germany (Deutsche WindGuard, 2025).

While the precise impact of these factors remains uncertain, it is reasonable to define a scenario with a shorter lifetime distribution. The German onshore market provides a useful benchmark, as it has already experienced changes in feed-in tariffs alongside more favourable repowering conditions. Accordingly, the fitted Weibull function for Germany (Kramer et al., 2024; Kramer, 2025) is adopted, with parameters $\lambda = 26$ and $k = 12$.

Onshore wind – longer lifetime scenario

A longer lifetime scenario is introduced to account for conditions that may lead to later decommissioning compared to the BAU scenario. In contrast to the shorter lifetime case, the BAU Weibull function is only marginally adjusted to reflect a slower depletion rate. Accordingly, Weibull parameters are set to $\lambda = 35$ and $k = 12$.

Insights from the research review indicate that there is currently no clear consensus on the maximum technical lifetime of onshore wind turbines in the UK, as experience remains limited, with the oldest sites in the UK now being 33 years old. One key driver for extended operation is the presence of grid and height constraints, which may limit repowering potential at certain sites.

Technical lifetime is influenced by multiple factors including turbine model, O&M strategy and the actual experienced load conditions. Furthermore, newer turbine designs are already engineered for lifetimes of 25 years with potential extensions to 35 years (e.g. Nordex 6.2 MW). This supports the plausibility of a longer lifetime scenario, even when considering only installations up to 2027 within the scope of this study.

The feasibility of a longer lifetime also depends on factors such as spare parts availability, development of revenues for selling the generated power and land lease agreement. In this regard, refurbishment and remanufacturing capacities are important as well as improved O&M practices, e.g. use of smart data to enable predictive maintenance. Going forward, further research is recommended to better understand technical limits and develop technologies to enable lifetime extensions of the existing fleet and future installations.

Offshore wind – BAU, shorter lifetime and longer lifetime scenario

As outlined by Abrahamsen et al. (2023) and Mc Govern et al. (2025), sufficient data to directly fit a Weibull function to the ratio of decommissioned to installed capacity by installation year is not available for offshore wind. Consequently, their approach for defining a BAU scenario is to shift the onshore Weibull function to reflect a longer assumed design life for offshore turbines.

Applied to the UK context, this approach would imply that 50% of the wind turbines in the fleet are expected to be decommissioned after approximately 37 years. However, the current fleet composition suggests substantial heterogeneity in turbine sizes: 46.6% of turbines in this study have an installed capacity of 6 MW or less, increasing to 58.9% below 8 MW and 73.9% below 10 MW. This indicates that a single lifetime assumption may mask important differences between early and more recent generations of offshore wind farms. The research review suggests typical design lifetimes of 25–30 years for first-generation offshore wind farms, while more recent projects are increasingly designed for lifetimes of 25–35 years (see section 2.1.1). However, extended operation remains highly dependent on economic conditions, particularly the balance between revenues and operating expenditures, which is currently subject to significant uncertainty in the UK. (see section 2.1.1.1.2).

B.1.4 Component replacement rates

Given existing data limitations and uncertainties regarding future developments, this study applies constant annual failure rates per turbine, consistent with the state-of-the-art approach adopted in the literature (Shammugam et al., 2019; Tota-Maharaj et al., 2021; Godoy León et al., 2025; and Carrol et al., 2015). This approach is suitable for long-term, policy-oriented material flow analysis, whereas operational decision-making models would benefit from incorporating stochastic variability and time-dependent failure distributions (Anderson, 2024).

Only one material flow study was identified that explicitly modelled replacements to enable lifetime extensions of 10 years (Tota-Maharaj et al., 2021). In this study, and in the context of acknowledged data limitations, it is assumed that after 20 years of operation the nacelle, blades, and hub are replaced, while the tower and foundation are retained. However, the stakeholder responses suggest that, in the UK context, operators do not typically undertake planned large-scale component replacement or modernisation after the originally intended design lifetime (e.g. 20 years). Instead, components are generally repaired or replaced on a failure basis, provided that this remains economically viable (see section 2.1.2.2). Some stakeholders also indicated that improvements in monitoring and maintenance strategies are expected in the future.

The scope of this study is limited to major replacements of components, as these have the largest impact on labour, costs (Anderson 2024, p. 81, p.106), material use, and emissions. Blades, generators, and gearboxes are included, as these are identified in the literature as having both high failure rates and high material intensity, and therefore the largest influence on material flow outcomes (Andersen et al., 2015; Reder et al., 2016; Carrol et al., 2016; Anderson, 2024). By contrast, the tower, nacelle, and foundation/substructure are assumed not to be replaced during operation, as failure of these components would typically result in full turbine decommissioning. Accordingly, component replacements in this study affect only end-of-life material flows of steel and composite materials, while concrete flows remain unaffected.

To integrate major replacements into the material flow model of the UK wind fleet, annual replacement rates are first defined and subsequently translated into component-level material masses. This methodological approach is based on Shammugam et al. (2019), Godoy León et al. (2025), Andersen et al. (2015) and Tota-Maharaj et al. (2021).

Current literature on failure and replacement rates is difficult to compare due to a lack of harmonised terminology, and in many cases it is not clearly specified whether a failure leads to repair or full component replacement (see Table 46 in Appendix B: Material flow modelling). For instance, Dao et al. (2019) report that offshore wind turbine failure rates are approximately three times higher than onshore; however, their analysis does not distinguish between major repairs, minor repairs, and component replacements.

The annual replacement rates for gearboxes, generators, and blades used in this study are derived from the studies listed in Table 46 in Appendix B: Material flow modelling and differentiated between onshore and offshore wind.

For blades, the literature outlines the following annual replacement rates:

- Onshore: 2% (Faulstich et al., 2011), 2.2% (Andersen et al., 2015), 2.3% (Schreiber et al., 2019), consequently ranging 2.0%-2.3% and averaging at 2.2%
- Offshore: 0.1% (Carrol et al., 2016), 3% (Avanessova, 2023). After sense checking with ORE Catapult researchers, 0.1% is considered an outlier

For the generator, the following annual replacement rates are reported:

- Onshore:
 - 1% (DFIG), 1.8% (DD-EESG), 1.21% (DD-PMSG) (Schreiber et al. 2019),
 - 2.9% (Andersen et al., 2015),
 - 2% for direct drive and 4% for generator (Faulstich et al. 2011),
 - 0.7% (HS-PMSG), 0.8% (GB-PMSG), 0.9% (DD-PMSG) to 10.9% (DFIG, DD-EESG, SCIG) (Shammugam et al., 2019)
 - In summary, values range between 0.7%-10.9%, averaging at 2.6%.
- Offshore:
 - 0.3% (Avanessova, 2023)
 - 0.7% (HS-PMSG), 0.8% (GB-PMSG), 0.9% (DD-PMSG) to 10.9% (DFIG, DD-EESG, SCIG) (Shammugam et al., 2019; Godoy León et al., 2025)
 - 1.0% geared drive train system and 2.1% direct drive system (Donnelly et al., 2024)
 - 9.5% (Carrol et al., 2016)
 - In summary, values range between 0.3%-10.9%, averaging at 3.3%.

Finally, for the gearbox, annual replacement rates per turbine vary between sources as follows:

- Onshore: 3% (Faulstich et al., 2011), 3.1% (Andersen et al., 2015), 4.2% (single stage, Shammugam et al., 2019), 4.8% (Schreiber et al., 2019), 5.1% (Godoy León et al., 2025) and 5.9% (multiple stage, Shammugam et al., 2019). Hence, ranging between 3.1%-5.9% and an average of 4.6%.
- Offshore: 0.9% (Avanessova, 2023), 2.2% (Donnelly et al., 2024), 4.2% (single stage, Shammugam et al., 2019), 5.1% (Godoy León et al., 2025), 5.9% (multiple stage, Shammugam et al., 2019) and 15.4% (Carrol et al., 2016). Consequently, ranging between 0.9%-15.4% and averaging at 5.6%.
- One stakeholder reported that direct drive turbines are easier to maintain, due to not having a gearbox as a point of maintenance or failure (see section 2.1.2.1).

The wide variation in reported values can be explained by differences in turbine design, operation and maintenance strategies, environmental conditions, and turbine age across the underlying studies. Table 11 summarised the assumptions made in the material flow model.

Trends observable in the data table are that gearboxes fail most, followed by generators and then blades, and that failure rates are generally higher offshore than onshore.

For all scenarios (BAU, shorter lifetime, and longer lifetime), the same replacement parameters are applied, while the size of the operational fleet varies according to lifetime assumptions. In the lifetime extension scenarios, sensitivity analysis is used to capture the impact of increased replacement activity associated with an ageing fleet.

It should be noted that for a comprehensive assessment of the material impacts it should be distinguished whether the replacements take place with new or second-lifecycle components (reused, repaired, refurbished or remanufactured). Stakeholder interviews indicate that procurement decisions depend on availability, cost, and quality, with increasing likelihood of sourcing second-life components as turbines age. Compared to new component manufacturing (often overseas), reuse and refurbishment can reduce waste generation and improve lifecycle emissions, as well as increase domestic GVA and employment in the UK. This is further discussed in section 3.1.2.2.2.

B.1.5 Turbine and component reuse

Scenarios for the fraction of second lifecycle pathways

The first step in decision-making is to assess whether the decommissioned wind turbines, components or parts can be resold, as this is usually also financially the most attractive pathway. According to findings of the literature review (Struthers and Pitts, 2025) and the stakeholder interviews (see section 2.5.1), the UK is an active participant in the second-hand market, both as a buyer and seller of onshore wind turbines, components, and parts.

To approximate the potential fraction of wind turbines entering a second lifecycle, this study applies the approach by Kramer et al. (2024) and Kramer (2025, pp. 156-162), originally developed for onshore wind, and adapts it to the UK context based on additional literature (Struthers and Pitts, 2025 and research review findings). Scenario-based estimates are derived for each material flow, distinguishing between onshore and offshore wind.

Reuse potential of the foundation/substructure

In cases of partial or full removal, onshore wind turbine foundations are assumed not to enter a second lifecycle and are instead treated as waste. The same assumption is applied to offshore foundations and substructures.

As a result, concrete quantities from the removal of onshore wind foundations and the foundation of the Blyth Offshore Demonstrator phase 1 are expected to directly enter waste handling. Consequently, concrete is not considered further in the discussion of second lifecycle pathways.

In addition to the large concrete volumes, onshore foundations contain a relatively small share of steel and iron, approximately 4% of total foundation mass (Tota-Maharaj et al., 2021). This represents only a minor contribution to the overall steel and iron mass of a wind turbine, which

is primarily concentrated in the tower and nacelle. By contrast, offshore foundations account for a substantial share of total steel and iron mass. For the offshore fleet considered in this study, this ranges from approximately 34% to 82%, depending on foundation type and water depth. As these structures are excluded from second lifecycle pathways, this significantly reduces the overall potential for reuse and other higher-value circular economy options within the offshore sector.

Reuse potential of the whole turbine or key components

For onshore wind, reuse of wind turbines is increasingly seen as a realistic option, particularly for smaller models constrained by planning restrictions (see section 2.5.1). For offshore wind, no practical experience with turbine reuse currently exists, however Struthers and Pitts (2025) highlight potential for the UK fleet.

With regard to component reuse, most experience in the UK, particularly for offshore, stems from handling replaced components and parts during O&M activities. While UK-wide statistics are not available, stakeholder interviews indicate that refurbishment of components, such as gearboxes, is a common practice, especially for ageing turbines (see section 2.1.1.1.4). The research review further suggests that reuse rates tend to be higher in the onshore sector than offshore.

Reuse rate estimation method

To derive an order of magnitude for an upper reuse fraction of the current installed onshore and offshore fleet in the UK, the following criteria are applied (Kramer, 2025, pp. 156-162):

1. Retain turbine models with more than 50 units in operation, as a proxy for spare parts availability
2. Retain turbines from OEMs that are still active or have been consolidated, to ensure access to maintenance, repair, and operations (MRO) services
3. Retain pitch-regulated turbines, to reflect grid compliance requirements
4. Consider the Weibull distribution of each lifetime scenario and the balance between decommissioning and component replacement when defining reuse scenarios

To approximate spare parts availability, it is assumed that turbine models with more than 50 units in operation have sufficient access to spare parts. This represents a simplified assumption, as it does not account for potential sourcing from international decommissioning streams. To address this limitation, offshore turbine models with fewer than 50 units installed in the UK are cross-checked against the analysis by Struthers and Pitts (2025) to determine whether they are widely deployed in the UK onshore market or in other European offshore markets before being excluded.

Figure 68 and Figure 69 show the distribution across turbine models for onshore and offshore installations in the UK. Given the large amount of different turbine models, the figure for

onshore only shows the top 20, while for offshore all installed models are shown. The application of the first criteria results to keeping ~73%-77% of the onshore fleet.

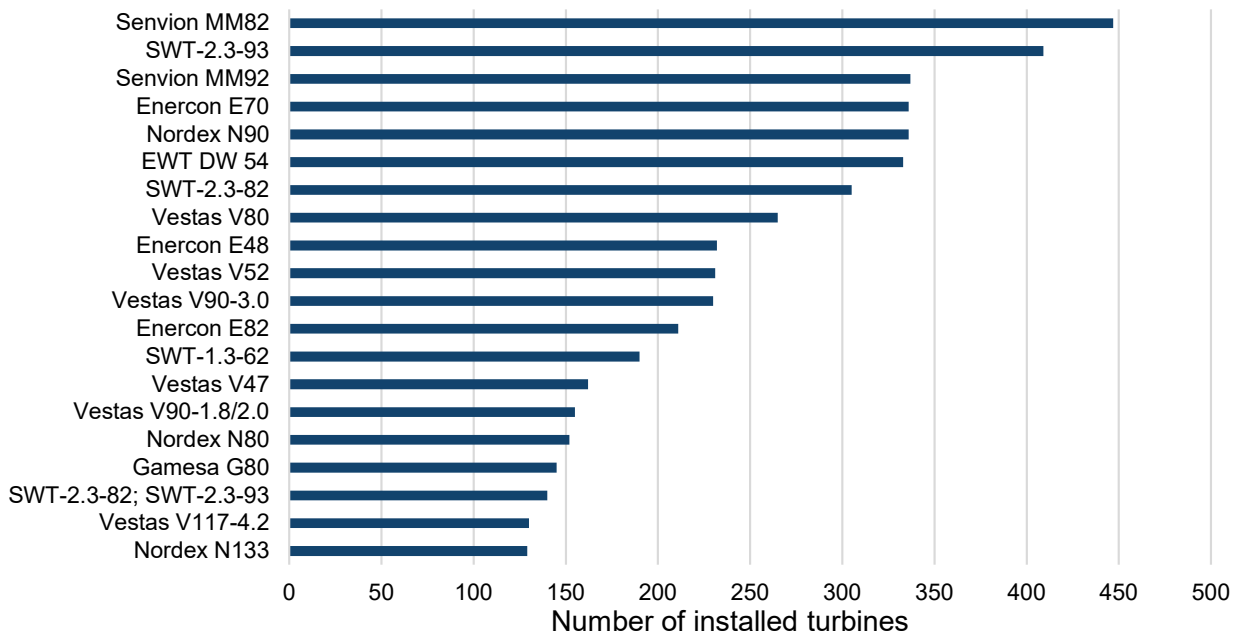


Figure 68: Distribution of top 20 installed turbine models of the onshore wind turbine fleet in the UK by number of turbines. Own calculation, based on Renewables UK data.

For the offshore fleet, the application of this filter criteria results in excluding 6 of the 22 installed wind turbine types. When in accounting for the installations in the UK onshore market or other European offshore markets, only 4 turbine models are excluded, that results to keeping 99% of the total installed offshore wind turbines.

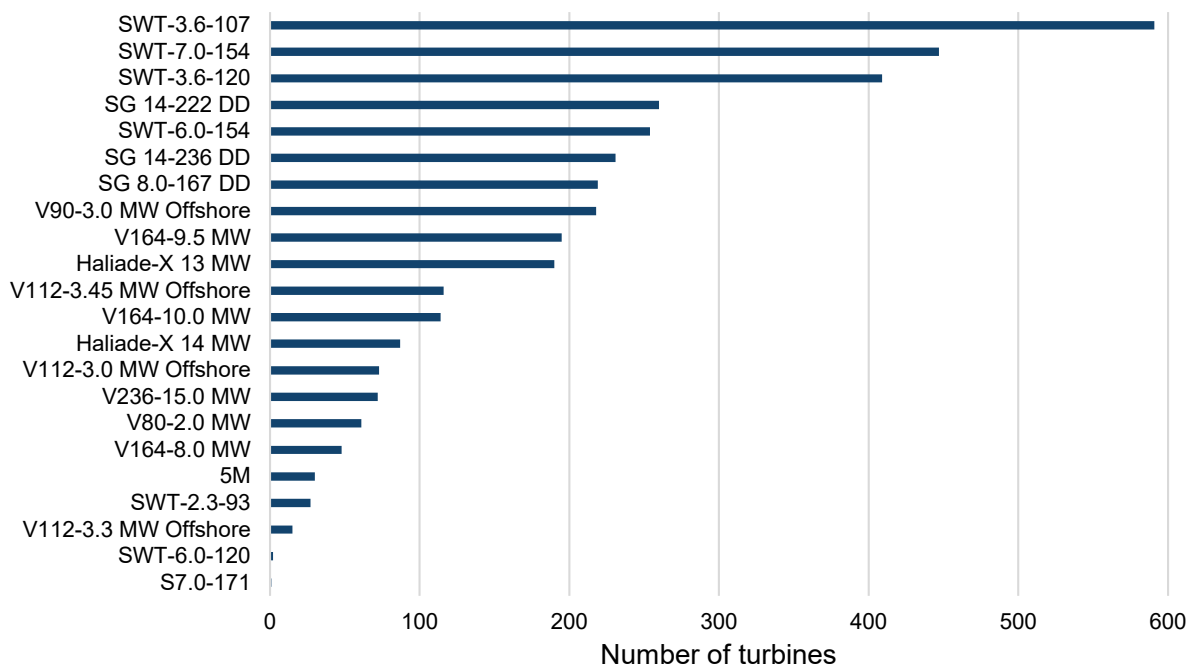


Figure 69: Distribution of turbine models of the offshore wind turbine fleet in the UK. Own calculation, based on ORE Catapult and 4C Offshore data.

Secondly, to anticipate access to MRO services, it is assumed that turbine models originating from OEMs that no longer exist or have not merged with a large OEM are unlikely to have access to such services, either in the UK or internationally. In contrast, OEM companies that have been operating under the same brand for an extended period (e.g. Enercon, Vestas) seem to be favoured on the second-hand market (Kramer, 2025, p. 105, 158). However, this is not incorporated into the modelling at this stage. A similar trend may also be observed in other sectors, such as automotive (Kramer, 2025, p. 158). Applying this criteria results in retaining 72%-76% of the onshore fleet, and no further exclusions for the offshore fleet.

Thirdly, to anticipate grid code compliance, very old turbines that operate with stall regulation rather than a pitch system are excluded. Determining what additional proportion of the fleet may be subject to grid compliance constraints, both in the UK and export markets, requires further analysis of the national grid code requirements and potential upgrade solutions. Applying this third criteria results in retaining 68%-72% of the onshore fleet, and no further exclusions for the offshore fleet. This range can be interpreted as an upper ratio for potential reuse, as further factors such as remaining life, economic feasibility and demand at time of decommissioning influence the reuse potential (Kramer, 2025).

Finally, rates are defined for the three lifetime scenarios considered in this study. The majority of material flows stem from decommissioning, followed by component replacements during operation.⁸ For the reuse potential, the following assumptions are made:

- For the estimated flows from decommissioned wind turbines, it is assumed that the earlier lifetime scenario has the highest reuse potential, followed by the BAU scenario and then the longer lifetime scenario. As such, the potential reuse fractions resulting from the three filter steps were further reduced to account for a fraction of the fleet anticipated to have insufficient remaining useful life.
- For components handled from O&M replacements, the reuse potential in the longer lifetime scenario is expected to be the largest, followed by the BAU scenario and then the shorter lifetime scenario. This reflects the increased demand for second-lifecycle components as turbines age, due to the reduced availability of new components.

Table 47 summarises the assumption made for the onshore and offshore wind turbine fleet.

⁸ Please refer to chapter 3.2.2 for the mass breakdown between component replacements and decommissioning per scenario and distinguishing between onshore and offshore wind.

Table 47: Overview of second lifecycle assumptions of scenarios. Method based on Kramer (2025), assumptions additionally informed by Struthers & Pitts (2025), phase 2 findings and UK's fleet characteristics.

	Onshore	Offshore
Business as usual scenario	0% concrete mass ~21% steel & iron mass ~21% composite mass	0% concrete mass 0% steel & iron mass from foundation ~12% steel & iron mass from wind turbine ~12% composite mass
Shorter lifetime scenario	0% concrete mass ~26% steel & iron mass ~26% composites mass	0% concrete mass 0% steel & iron mass from foundation ~19% steel & iron mass from wind turbine ~19% composite mass
Longer lifetime scenario	0% concrete mass ~13% steel & iron mass ~13% composite mass	0% concrete mass 0% steel & iron mass from foundation ~10% steel & iron mass from wind turbine ~10% composite mass
Sensitivity of base assumption	-10% of second lifecycle fraction +10% of second lifecycle fraction +20% of second lifecycle fraction For the foundations the assumption to directly enter waste handling is not changed	

As outlined, data on the reuse potential of the UK wind turbine fleet is currently lacking, making it difficult to define a base assumption for each scenario. Therefore, the resulting estimates are presented as ranges, considering the sensitivities from Table 47 (see section 3.2.4).

B.1.6 Material recovery

The recovery, export, and non-recovery rates for steel and iron identified in the research review (see section 2.4.1) and stakeholder interviews (see section 2.4.2.2.2) are presented in Table 48. On this basis, a baseline assumption of 95% material recovery and 5% non-recovery was selected, which represents the maximum potential for the UK. To account for a majority being exported, additional sensitivity scenarios are defined, assuming that 25%, 50%, 75%, or 95% of the steel and iron mass is exported, with correspondingly lower domestic recovery rates.

Table 48: Overview of fractions on material recovery and no recovery for steel & iron waste.

Steel and iron waste				
Study	Scope	Material Recovery	No Material Recovery	Comment
ZWS (2023)	UK construction steel	97%	3%	High fraction is exported.
Tota-Maharaj et al. (2021), business as usual	UK onshore and offshore wind	90%	10%	Citing various LCAs and the assumption of a 10% loss.
		87%	13%	If foundation is not removed, a loss of an average of 13% of total steel and iron content for onshore wind turbines is assumed.
LCA Vestas V150-4.2 MW (2019)	V150-4.2 MW	92%	8%	-
LCA Vestas V112-3.3 MW (2022)	V112-3.3 MW	92%	8%	-
Jiang et al. (2025)	Onshore wind	98.16%	1.84%	Based on three studies
Heidak et al. (2025)	Onshore wind	90%	10%	Based on Schreiber et al.
Phase 2 stakeholder interviews		Recycling perceived as being well established. Majority exported to Europe for smelting and then reimported into the UK as manufactured products.		
Assumption in material flow model		95% material recovery / 5% no recovery (maximum potential for the UK) To account for a majority being exported: 75% material recovery UK / 25% export 50% material recovery UK / 50% export 25% material recovery UK / 75% export 5% material recovery UK / 95% export		

Concrete is commonly recovered via downcycling and used in the construction sector as aggregate filler (ZWS, 2023; Jiang et al. 2025). In cases where the material is contaminated, landfilling may be required. Moreover, the remainder of the studies shown in Table 49 assume landfilling at the project site due to a non-removal of the foundation. According to the findings from the stakeholder interviews, at least a partial removal seems to be common practice for onshore installations, while practice for offshore it is still to be defined. Consequently, a scenario of 100% landfilling is not considered as a base assumption but rather included as a sensitivity case. A baseline assumption of 50% material recovery and 50% no recovery is set. To account for the uncertainties related to estimating future developments, further sensitivities are included (100% / 75% / 25% / 0% material recovery).

Table 49: Overview of fractions on material recovery and no recovery for concrete waste.

Concrete				
Study	Scope	Material Recovery	No Material Recovery	Comment
ZWS (2023)	UK hard construction & demolition waste	90%, downcycling	10%	-
Tota-Maharaj et al. (2021), business as usual	UK onshore and offshore wind	0%	100%	Assuming no removal of foundation
LCA Vestas V150-4.2 MW (2019)	V150-4.2 MW	0%	100% landfill	-
LCA Vestas V112-3.3 MW (2022)	V112-3.3 MW	0%	100% landfill	-
Jiang et al. (2025)	Onshore wind	50%, downcycling	50%	Based on three studies
Phase 2 stakeholder interviews		No clear fraction derived, but either landfilling at project site (due to not fully removing foundation) or grinding or crushing a reuse in concrete materials or secondary fillers		

Concrete				
Study	Scope	Material Recovery	No Material Recovery	Comment
Assumption in material flow model		100% material recovery / 0% no recovery 75% material recovery / 25% no recovery 50% material recovery / 50% no recovery (base assumption) 25% material recovery / 75% no recovery 0% material recovery / 100% no recovery		

For composite material recovery, the research review provided the results shown in Table 50. A baseline assumption of 50% material recovery and 50% non-recovery is applied. These are comparatively higher recovery rates than those reported in most of the reviewed studies. Nevertheless, this assumption is supported by insights from stakeholder interviews, which identified mechanical recycling as an emerging practice. In addition, increasing attention is being directed toward composite recycling within the wind industry, particularly following commitments to achieve zero landfilling of turbine blades.

Table 50: Overview of fractions on material recovery and no recovery for composite waste.

Composite				
Study	Scope	Material Recovery	No Material Recovery	Comment
ZWS (2023)	Scotland, onshore	Max 40%, downcycling	Min 60%	-
Tota-Maharaj et al. (2021), business as usual	UK onshore and offshore wind	0%	100%	Landfilling assumed, based on various LCA studies
Tota-Maharaj et al. (2021), improved practices	UK onshore and offshore wind	20%, downcycling	80%	Mechanical recycling, recycled into aggregate

Composite				
Study	Scope	Material Recovery	No Material Recovery	Comment
University of Strathclyde (2014)	UK glass fibre recycling	0%	98%	-
LCA Vestas V150-4.2 MW (2019)	V150-4.2 MW	0%	100%	50% incineration & 50% landfill
LCA Vestas V112-3.3 MW (2022)	V112-3.3 MW	0%	100%	50% incineration & 50% landfill
Jiang et al. (2025)	Onshore wind	0%	100%	Based on two studies
Heidak et al. (2025)	Onshore wind	0%	100%	90% landfilled & 10% incinerated
Phase 2 stakeholder interviews		Limited options available to asset owners in the UK. Preference for mechanical recycling, alternatively incineration or landfilling. Repurposing also an option, but scale unclear.		
Assumption in material flow model		100% material recovery / 0% no recovery 75% material recovery / 25% no recovery 50% material recovery / 50% no recovery (base assumption) 25% material recovery / 75% no recovery 0% material recovery / 100% no recovery		

B.2 Material flow assumptions

B.2.1 Onshore wind

Fleet data: RUK database (31/12/2025) – Most comprehensive dataset of UK's onshore fleet that is available.

Table 51: Onshore wind calculation of material quantities.

Parameter	Assumption
Material quantities	Not included in RUK dataset, therefore calculated as follows:
Composites of blades	RUK dataset provides for majority of wind turbines the information on rotor diameter. Thus, applying the regression function by Abrahamsen et. al (2023). Rest via function (considering MW) of Tota-Maharaj et al. (2021).
Concrete of foundation	RUK dataset doesn't provide information on foundation type/depth. Regression function by Tota-Maharaj et al. (2021), developed for UK market, applied.
Steel and iron	Regression function by Tota-Maharaj et al. (2021), developed for UK wind market, applied. This function doesn't differentiate between key components.

Table 52: Onshore wind expected time of decommissioning and time of operation.

Parameter	Assumption
Approach	Depletion of fleet according to accumulated Weibull function, based on Abrahamsen et al. (2023), Kramer et al. (2024), Kramer (2025), McGovern et al. (2025).
BAU scenario	Weibull $\lambda = 33$, $k = 12$ (fitted to ratios of decommissioning over installed capacity per installation year) --> BAU already operates in a lifetime extension mode.
Shorter lifetime scenario	Weibull $\lambda = 26$, $k = 12$ (towards German Weibull function)
Longer lifetime scenario	Weibull $\lambda = 35$, $k = 12$

Table 53: Onshore wind component replacements during turbine operation.

Parameter	Assumption
Blades	2.2% per turbine per year
Generator	2.6% per turbine per year
Gearbox	4.6% per turbine per year

Table 54: Onshore wind decommissioning: removal from project site.

Parameter	Assumption
Wind turbine	100% of wind turbine removed from project site
Foundation	100% of foundation removed
Variation across scenarios	A few experts (phase 2) provided information and it seems that partial removal of the foundation is the current common practice in the UK. Not known from RUK dataset how many shallow and deep foundations are installed in the UK. Thus, keeping 100% in the model and hence model shows maximum amount of materials to be handled.

Table 55: Onshore wind handling of decommissioned wind turbines, foundations and replaced major components during operation.

Parameter	Assumption
Approach	Constant ratios are defined, also introducing the option to handle via second-hand market. However, data is limited for decommissioned quantities and for replacements during O&M common practice is to refurbish, but also limited data available. Further detailed analyses and research recommended.

Parameter	Assumption
Second lifecycle as entire turbine or component	0% for foundation, thus 0% for concrete. 21% (BAU) / 26% (shorter life scenario) / 13% (longer life scenario) for second lifecycle fraction of steel & iron mass and composite mass, either reuse as entire turbine or as spare parts
Material recovery	<ul style="list-style-type: none"> - 50% material recovered of concrete - 95% material recovered of steel & iron - 50% material recovered of composite
No material recovery	<ul style="list-style-type: none"> - 50% no material recovered of concrete - 5% no material recovered of steel & iron - 50% no material recovered of composite

B.2.2 Offshore wind

Fleet data: ORE Catapult database – Dataset of UK's offshore fleet is based on 4C Offshore with additional information on material quantities by ORE Catapult.

Table 56: Offshore wind calculation of material quantities.

Parameter	Assumption
Material quantities	Included in ORE Catapult dataset
Composites of blades	Detailed data on material composition of blades of turbines with different installed capacities (1 MW up to 20 MW).
Concrete of foundation	Distinguish between monopile, jacket, floating wind. Concrete only in one operational wind farm in the UK.
Steel and iron	Detailed data on material composition of key components in nacelle, tower and distinguish between monopile, jacket and floating wind for foundation.

Table 57: Offshore wind expected time of decommissioning and time of operation.

Parameter	Assumption
Approach	Set decommissioning year per wind farm for BAU, shorter and longer lifetime scenarios.
BAU scenario	30 years project life per wind park
Shorter lifetime scenario	25 years project life per wind park
Longer lifetime scenario	35 years project life per wind park

Table 58: Offshore wind component replacements during turbine operation.

Parameter	Assumption
Blades	3.0% per turbine per year
Generator	3.3% per turbine per year
Gearbox	5.6% per turbine per year

Table 59: Offshore wind decommissioning: removal from project site.

Parameter	Assumption
Wind turbine	100% of wind turbine removed from project site
Foundation	100% of foundation removed
Variation across scenarios	No standard defined yet & almost no experience in offshore decommissioning (worldwide). Therefore assume 100% removal for now. This may vary in the future across projects, depending on impact assessment of site. Consequently, MFA shows maximum amount of materials to be handled.

Table 60: Offshore wind handling of decommissioned wind turbines, foundations and replaced major components during operation.

Parameter	Assumption
Approach	Constant ratios are defined, also introducing the option to handle via second-hand market. However, no experience yet in the UK for handling decommissioned quantities; for replacements during O&M common practice is to refurbish, but also limited data available. Further detailed analyses & research recommended.
Second lifecycle as entire turbine or component	0% for foundation, thus 0% for concrete and 0% for steel & iron mass of foundation. 12% (BAU) / 19% (shorter life scenario) / 10% (longer life scenario) for second lifecycle fraction of steel & iron mass in wind turbines and composite mass, either reuse as entire turbine or as spare parts
Material recovery	<ul style="list-style-type: none"> - 50% material recovered of concrete - 95% material recovered of steel & iron - 50% material recovered of composite
No material recovery	<ul style="list-style-type: none"> - 50% no material recovered of concrete - 5% no material recovered of steel & iron - 50% no material recovered of composite

B.2.3 Onshore and offshore wind

Operational fleet:

- Operational capacity in year n = Cumulative installed capacity in year $n-1$ + new installations in year n - decommissioning in year n
- No future installations in scope, thus fleet shrinks over time.

Component replacements during turbine operation:

- Failure rates, replacement rates, O&M activities to enable lifetime extensions, etc. remain a research gap. Common approach in literature applied: Constant replacement rate per turbine per year of component.
- Focus of MFA is on major replacements of blades, generator and gearbox, as most material intensive. Thus, minor repairs & major repairs out of scope.

- Masses of gearbox and generator needed and therefore average masses are calculated according to data from ORE Catapult.
- Constant replacement rates are defined on the basis of an extensive literature review (multiple sources) and discussions with researchers from ORE Catapult.
- Rates distinguish between onshore & offshore, acknowledging for slightly higher observed failure rates in offshore in comparison to onshore.
- Not possible to determine how rates change across scenarios - change across turbine age - as there is no data available on failure and replacement rates beyond the age of 10 years.
- From phase 2, most interviewed operators do not operate in a predictive maintenance mode and do not plan any specific upgrades/replacements to enable lifetime extension.
- Using refurbished components is a common practice, which would reduce material demand for component replacements.
- Due to research gap, same replacements rates across BAU, shorter and longer life scenarios. Hence, variations of material quantities stem from different operational lifetimes of scenarios.
- Sensitivity analysis with varying annual replacement rates.

Handling of decommissioned wind turbines, foundations and replaced major components during operation:

- Material recovery vs no material recovery remains the same across scenarios.
- Second lifecycle ratio is likely to decrease with extending lifetime, however, data/research missing on technical limits per technology design (and how repair, part /component replacements, O&M strategy, etc. changes that). Demand on second-hand market varies depending on turbine type (e.g. whether this type is still frequently installed, thus demand for spare parts) and as such rates for each lifetime scenario were defined based on fleet characteristics, Kramer (2025), ORE Catapult (2025) and the phase 2 findings. Moreover, sensitivity analyses with different ratios of second hand/material recovery/no material recovery were conducted.

Table 61: Onshore and offshore wind scope.

Parameter	Assumption
Fleet	UK's onshore and offshore wind turbine fleet of installed wind turbines and wind parks under construction. Hence, future installations are out of scope

Parameter	Assumption
Wind technology	<ul style="list-style-type: none"> - Onshore and offshore wind turbines and foundations. Other infrastructure such as external cables, substations or scour protection are out of scope. - Common turbine type of horizontal axis turbine with three blades, and for onshore also some wind turbines with two blades - Turbines with a minimum installed capacity of 50 kW. Thus, household wind turbines are out of scope.
Selected materials	<ul style="list-style-type: none"> - Steel of wind turbine and foundation/substructure - Concrete of foundation/substructure - Composites of blades

B.3 Material flow sensitivities

Table 62: Onshore and offshore wind variation of recovery/no recovery fraction of blade composite - total material recovered ⁹ (1990 – 2070).

Sensitivity parameter	Total composite material recovered (tonnes)					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
100% recovery composites	279,892	239,360	315,900	593,948	503,543	655,401
75% recovery composites	209,919	179,520	236,925	445,461	377,657	491,551
25% recovery composites	69,973	59,840	78,975	148,487	125,886	163,850
0% recovery composites	-	-	-	-	-	-

⁹ No material recovery is in the reverse order of recovered material for all scenarios.

Table 63: Onshore wind variation of recovery/no recovery fraction of steel and iron - total material recovered and not recovered (1990 – 2070).

Sensitivity parameter	Total steel and iron material recovered and not recovered (Mt)					
	Material Recovery			No Material Recovery		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
75% recovery steel and iron	2.0	1.8	2.2	0.7	0.6	0.7
50% recovery steel and iron	1.3	1.2	1.5	1.3	1.2	1.5
25% recovery steel and iron	0.7	0.6	0.7	2.0	1.8	2.2
5% recovery steel and iron	0.1	0.1	0.1	2.4	2.2	2.8

Table 64: Offshore wind variation of recovery/no recovery fraction of steel and iron - total material recovered and not recovered (2004 – 2065).

Sensitivity parameter	Total steel and iron material recovered and not recovered (Mt)					
	Material Recovery			No Material Recovery		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
75% recovery steel and iron	8.0	7.7	8.1	2.7	2.6	2.7
50% recovery steel and iron	5.3	5.1	5.4	5.3	5.1	5.4
25% recovery steel and iron	2.7	2.6	2.7	8.0	7.7	8.2
5% recovery steel and iron	0.5	0.5	0.5	10.1	9.8	10.3

Table 65: Onshore changing ratios of second-hand for steel, iron and composites – total material reuse (1990 – 2070).

Sensitivity parameter	Total material reuse (Mt)					
	Steel and Iron			Composite		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Second lifecycle fraction -10%	0.4	0.5	0.1	0.04	0.05	0.01
Second lifecycle fraction +10%	1.0	1.1	0.8	0.1	0.1	0.08
Second lifecycle fraction +20%	1.4	1.5	1.1	0.1	0.1	0.1

Table 66: Offshore changing ratios of second-hand for steel, iron and composites – total material reuse (2004 – 2065).

Sensitivity parameter	Total material reuse (Mt)					
	Steel and Iron			Composite		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Second lifecycle fraction -10%	0.09	0.4	-	0.01	0.06	-
Second lifecycle fraction +10%	1.0	1.3	0.9	0.1	0.2	0.1
Second lifecycle fraction +20%	1.5	1.8	1.5	0.2	0.2	0.2

Table 67: Onshore changing ratios of second-hand for steel, iron and composites – total material recovered (1990 – 2070).

Sensitivity parameter	Total material recovered (Mt)					
	Steel and Iron			Composite		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Second lifecycle fraction -10%	2.8	2.5	3.0	0.2	0.1	0.2
Second lifecycle fraction +10%	2.2	1.9	2.4	0.1	0.1	0.1
Second lifecycle fraction +20%	1.8	1.6	2.1	0.1	0.09	0.1

Table 68: Offshore changing ratios of second-hand for steel, iron and composites – total material recovered (2004 – 2065).

Sensitivity parameter	Total material recovered (Mt)					
	Steel and Iron			Composite		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Second lifecycle fraction -10%	10.6	10.2	10.8	0.3	0.3	0.4
Second lifecycle fraction +10%	9.7	9.3	9.9	0.3	0.2	0.3
Second lifecycle fraction +20%	9.3	8.9	9.4	0.2	0.2	0.3

Table 69: Onshore changing ratios of second-hand for steel, iron and composites – total material not recovered (1990 – 2070).

Sensitivity parameter	Total material not recovered					
	Steel and Iron			Composite		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Second lifecycle fraction -10%	0.1	0.1	0.2	0.2	0.1	0.2
Second lifecycle fraction +10%	0.1	0.1	0.1	0.1	0.1	0.1
Second lifecycle fraction +20%	0.1	0.09	0.1	0.1	0.09	0.1

Table 70: Offshore changing ratios of second-hand for steel, iron and composites – total material not recovered (2004 – 2065).

Sensitivity parameter	Total material not recovered (Mt)					
	Steel and Iron			Composite		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Second lifecycle fraction -10%	0.6	0.5	0.6	0.3	0.3	0.4
Second lifecycle fraction +10%	0.5	0.5	0.5	0.3	0.2	0.3
Second lifecycle fraction +20%	0.5	0.5	0.5	0.2	0.2	0.3

Appendix C: Economic impact assessment

C.1 Economic modelling methodology

Table 71: GVA ratios for onshore turbines.

Activities	GVA ratio	Calculations
Operations & Maintenance	£19,483,200 per GW	<p>The GVA per FTE in 2019 was £180,000 (BVG Economics, 2019).</p> <p>The inflation factor between 2019 and 2024 is 1.23 (HM Treasury, 2026).</p> <p>The GVA per FTE in 2024 is £221,400.</p> <p>The number of FTE per GW is 88 (Almqvist et al., 2023).</p> <p>The GVA per GW is £19,483,200.</p> <p>GVA from O&M activities is calculated for comparison purposes and serves as an indicative measure only.</p>

Replacement of parts (blade)	£79,000 per blade	<p>Estimation #1¹⁰</p> <p>GVA = Output – Intermediate consumption</p> <p>Output: £103,000</p> <ul style="list-style-type: none"> - Labor: £52,000 - Crane: £22,000 - Transportation: £23,000 - Materials & tools: £6,000 <p>Intermediate consumption: £44,000</p> <ul style="list-style-type: none"> - Labor: £0 - Crane: £19,000 - Transportation: £20,000 - Materials & tools: £5,000 <p>GVA service firm = £103,000 - £44,000 = £59,000</p> <p>GVA crane rental firm = £19,000 x 56.3% (SIC 77.32) = £10,697</p> <p>GVA transport firm = £20,000 x 45.5% (SIC 49.41) = £9,100</p> <p>GVA component manufacturing firms = £0 (not manufactured in UK, assumption)</p> <p>Total GVA = £79,000</p>
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¹⁰ Interview of stakeholder 3_04

Replacement of a generator	£60,000 per turbine	<p>Estimation #1¹¹</p> <p>GVA = Output – Intermediate consumption</p> <p>Output: £69,000</p> <ul style="list-style-type: none"> - Labor: £51,000 - Crane: £8,000 - Transportation: £6,000 - Materials & tools: £4,000 <p>Intermediate consumption: £15,000</p> <ul style="list-style-type: none"> - Labor: £0 - Crane: £7,000 - Transportation: £5,000 - Materials & tools: £3,000 <p>GVA service firm = £69,000 - £15,000 = £54,000</p> <p>GVA crane rental firm = £7,000 x 56.3% (SIC 77.32) = £3,941</p> <p>GVA transport firm = £5,000 x 45.5% (SIC 49.41) = £2,275</p> <p>GVA component manufacturing firms = £0 (not manufactured in UK, assumption)</p> <p>Total GVA = £60,000</p> <p>Estimation #3¹² (not used)</p> <p>Cost: £0.75 million for a 2.5 MW onshore turbine generator refurbishment and replacement, including cranes, personnel and parts.</p> <p>Generator mass: 6.7 tonnes (Siemens Wind Power, 1999)</p> <p>Estimation #4 (not used)</p>
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		Cost of a refurbished generator: £12,500 (MWPS, 2026) (VESTAS V66 Generator – 1.65 MW RCC)
Replacement of a gearbox	£63,000 per turbine	<p>Estimation #1¹³</p> <p>GVA = Output – Intermediate consumption</p> <p>Output: £80,000</p> <ul style="list-style-type: none"> - Labor: £51,000 - Crane: £9,000 - Transportation: £6,000 - Materials & tools: £14,000 <p>Intermediate consumption: £23,000</p> <ul style="list-style-type: none"> - Labor: £0 - Crane: £7,000 - Transportation: £5,000 - Materials & tools: £11,000 <p>GVA service firm = £80,000 - £23,000 = £57,000</p> <p>GVA crane rental firm = £7,000 x 56.3% (SIC 77.32) = £3,941</p> <p>GVA transport firm = £5,000 x 45.5% (SIC 49.41) = £2,275</p> <p>GVA component manufacturing firms = £0 (not manufactured in UK, assumption)</p> <p>Total GVA = £63,216</p>

¹¹ Interview of stakeholder 3_04.

¹² Interview of stakeholder 1_02.

¹³ Interview of stakeholder 3_04.

Decommissioning	£33,000 per MW	<p>Estimation #1 (Jacobs, 2025)</p> <p>GVA: £65,423 for a 2 MW turbine</p> <p>GVA: £32,711.5</p> <p>Estimation #2 (not used, incomplete data)</p> <p>Cost: €45,000 (£39,400) for the decommissioning of a 600 KW wind turbine (including foundation removal and revenue from scrap metal sales, but exclusive of blade management or waste treatment)</p> <p>Blade recycling cost: £1,000 per tonne (estimate)</p> <p>Cost of blade disposal: blade weight x £1,000 = 3 blades x 2.9 tonnes x £1,000 = £8,700 (estimate)</p> <p>GVA decommissioning (SIC 71.12): £39,400 x 51.7% = £20,163 (assuming that all decommissioning is completed in the UK)</p> <p>GVA blade recycling (SIC 38.32): £8,700 x 24.3% = £2,114</p> <p>Total GVA: £22,277</p> <p>GVA per MW: £22,277 x 100 / 60 = £37,128</p> <p>Estimation #3 (not used, incomplete data)</p> <p>Cost: €125,000 (£109,400) for the decommissioning of a 2,000 KW wind turbine (including foundation removal and revenue from scrap metal sales, but exclusive of blade management or waste treatment)</p> <p>Cost of blade disposal: blade weight x £1,000 = 3 blades x 11.3 tonnes x £1,000 = £33,900 (estimate)</p> <p>GVA decommissioning (SIC 71.12): £109,400 x 51.7% = £56,560 (assuming that all decommissioning is completed in the UK)</p> <p>GVA blade recycling (SIC 38.32): £33,900 x 24.3% = £8,238</p>
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		<p>Total GVA = £64,798</p> <p>GVA per MW: £64,798 x 100 / 200 = £32,399</p>
Part and turbine recovery	See GVA ratio for offshore turbines	Assumption: GVA per ton for recovering onshore parts and turbines is the same as for recovering offshore parts and turbines.
Material recovery (steel)	£209 per tonne	<p>In 2023, the UK steel industry contributed £2.3 billion to the UK economy in terms of GVA (Office for National Statistics, 2026).</p> <p>The UK produces approximately 10-11Mt of scrap steel each year (UK Steel, 2023).</p>
Material recovery (composites)	£680 per tonne	<p>FTE per tonne: 0.005</p> <p>GVA per FTE for recycling (SIC 38.32): £136,088</p> <p>GVA per tonne: £680</p>
Material recovery (concrete)	£68 per tonne	<p>FTE per tonne: 0.0005</p> <p>GVA per FTE for recycling (SIC 38.32): 136,088</p> <p>GVA per tonne: £68</p>

Table 72: GVA ratio for offshore turbines

Activities	GVA ratio	Calculations
Operations & Maintenance	£15,965,000 per GW (probably to low)	<p>Estimation #1</p> <p>The average GVA per FTE is £103,000 (DESNZ, 2025).</p> <p>The number of FTE per GW is 155 (Almqvist, 2023).</p> <p>The GVA per GW is £15,965,000.</p> <p>Estimation #2 (not used)</p> <p>Cost: About £47 million per annum for a 1 GW wind farm (BGV Associates, 2025).</p> <p>81% of total O&M spending for UK offshore wind projects is sourced domestically (Outer Dowsing Offshore Wind, 2025).</p>

Replacement of a blade	£0 per replacement	<p>Estimation #1¹⁴</p> <p>GVA = Output – Intermediate consumption</p> <p>Marine operations: 2 days (Avanessova, 2023)</p> <p>Labor: £32,000</p> <ul style="list-style-type: none"> - 6 technicians working on the turbine - 2 technicians on the vessel (estimate) - daily rate: £2,000 <p>The output other than labour (such as materials and tools, margins, etc.) has not been estimated.</p> <p>GVA service firm ≈ £32,000</p> <p>Standard Jack-Up hire: £720,000</p> <ul style="list-style-type: none"> - £360,000 per day (Jenkins et al., 2022) <p>GVA vessel operator = £720,000 x 26.6% (SIC 50.2)</p> <p>GVA component manufacturing firms = £0 (part not manufactured in UK)</p> <p>Major component replacement is assumed to be localised outside the UK (Pentland Floating Offshore Wind Farm, 2022)</p> <p>Total GVA = £0</p>
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¹⁴ Interview of stakeholder 4_02

Replacement of a gearbox	£0 per replacement	<p>Estimation #1¹⁵</p> <p>GVA = Output – Intermediate consumption</p> <p>Marine operations: 3 days (Avanessova, 2023)</p> <p>Labor: £48,000</p> <ul style="list-style-type: none"> - 6 technicians working on the turbine - 2 technicians on the vessel (estimate) - daily rate: £2,000 <p>The output other than labour (such as materials and tools, margins, etc.) has not been estimated.</p> <p>GVA service firm ≈ £48,000</p> <p>Standard Jack-Up hire: £1,080,000</p> <ul style="list-style-type: none"> - £360.000 per day (Jenkins et al., 2022) - Assumption: Jack-up vessels are predominantly owned and operated by non-UK companies. <p>GVA vessel operator = £1,080,000 x 26.6% (SIC 50.2)</p> <p>GVA component manufacturing firms = £0 (part not manufactured in UK)</p> <p>Major component replacement is assumed to be localised outside the UK (Pentland Floating Offshore Wind Farm, 2022)</p> <p>Total GVA = £0</p> <p>Cost of a new gearbox: £1.23 million</p> <ul style="list-style-type: none"> - A 5MW gearbox cost £700k to £1m, probably in 2010 (BGV Associates, 2025). - The inflation factor between 2010 and 2024 is 1.45 (HM Treasury, 2026). - A 5MW gearbox costs £1.01 million to £1.45 million in 2024.
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		<p>Estimation #2 (not used) (Mondor Intelligence, 2026)</p> <p>Project costs typically fall between £0.9 million to £1.3 million for a complete replacement.</p> <p>Estimation #3 (not used)</p> <p>The cost of a major repair was £334,500 in 2015 (Dinwoodie et al. 2015).</p> <p>The inflation factor between 2015 and 2024 is 1.33 (HM Treasury, 2026).</p> <p>The cost of a major replacement is £445,088 in 2024.</p> <p>The GVA of a major replacement is £227,885 (including non-UK GVA)</p>
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Replacement of a generator	£0 per replacement	<p>Estimation #1¹⁶</p> <p>GVA = Output – Intermediate consumption</p> <p>Marine operations: 4 days (Avanessova, 2023)</p> <p>Labor: £64,000</p> <ul style="list-style-type: none"> - 6 technicians working on the turbine - 2 technicians on the vessel (estimate) - daily rate: £2,000 <p>The output other than labour (such as materials and tools, margins, etc.) has not been estimated.</p> <p>GVA service firm ≈ £64,000</p> <p>Standard Jack-Up hire: £1,440,000</p> <ul style="list-style-type: none"> - £360.000 per day (Jenkins et al., 2022) - Assumption: Jack-up vessels are predominantly owned and operated by non-UK companies. <p>GVA vessel operator = £1,440,000 x 26.6% (SIC 50.2)</p> <p>GVA component manufacturing firms = £0 (part not manufactured in UK)</p> <p>Major component replacement is assumed to be localised outside the UK (Pentland Floating Offshore Wind Farm, 2022)</p> <p>Total GVA = £0</p> <p>Estimation #2 (not used)</p> <p>Cost: £2-4 million for an offshore turbine generator refurbishment and replacement, including cranes and personnel and parts</p>
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¹⁶ Interview of stakeholder 4_02

Decommissioning	£44,667 per MW	<p>Estimation #1 (Outer Dowsing Offshore Wind, 2025)</p> <p>Spend: £450 million</p> <p>Part of the decommissioning contract secured by UK: 18%</p> <p>UK GVA: £64 million</p> <p>Capacity: 100 x 15MW</p> <p>GVA per MW: £42,667</p> <p>Estimation #2 (Morgan Offshore Wind Ltd, 2024)</p> <p>Part of the decommissioning contract secured by UK: 18%</p> <p>UK GVA: £70 million</p> <p>Capacity: 1,500 MW</p> <p>GVA per MW: £46,667</p> <p>Estimation #3 (not used, incomplete)</p> <p>Decommissioning cost of a 500 MW offshore wind farm including contingency: £145 to 241 million</p> <p>Decommissioning cost per MW: £290,000 to 482,000 (Adedipe et al., 2021)</p> <p>Decommissioning cost per MW: €172,500 = £150,374 (TNO, 2025)</p>
Part and turbine refurbishment	£679 per tonne	<p>Estimation #1 (BVG Associates, 2023)</p> <p>GVA: £80 million (£876 million divided by 11 years)</p> <p>Mass: 11,731 tonnes (129,039 tonnes divided by 11 years)</p> <p>10% of mass refurbished</p> <p>GVA per tonne: £679</p>
Material recovery (steel)	£209 per tonne	See above.

Material recovery (composites)	£680 per tonne	See above.
Material recovery (concrete)	£68 per tonne	See above.

Table 73: Number of FTE ratio for onshore turbines

Activities	FTE ratio	Calculations
Operations & Maintenance	88 per GW (Almqvist, 2023)	Other sources provide different ratios: 100 (DESNZ, 2025), 56 (ClimateXChange, 2024), and 110 (NREL, 2020).
Replacement of blade	0.14 per turbine	<p>Estimation #1¹⁷</p> <p>Replacement of a Bonus 1.3 blade</p> <ul style="list-style-type: none"> - 6 days of project management and documentation - 1 site manager for 4 days - 4 technicians for 4 days - 5 days of mobilisation and demobilisation <p>Total: 31 days</p> <p>The replacement of a blade requires 0.14 FTE.</p> <p>Blade mass: 4.4 tonnes (Siemens Wind Power, 1999)</p>

¹⁷ Interview of stakeholder 3_03.

Activities	FTE ratio	Calculations
Replacement of a generator	0.136 per turbine	<p>Estimation #1¹⁸</p> <p>Replacement of a Bonus 1.3 generator</p> <ul style="list-style-type: none"> - 6 days of project management and documentation - 1 site manager for 5 days - 3 technicians for 5 days - 4 days of mobilisation and demobilisation <p>Total: 30</p> <p>The replacement of a generator requires 0.1364</p> <p>Estimation #2¹⁹ (not used)</p> <p>Replacement of a Bonus 1.3 generator</p> <ul style="list-style-type: none"> - A team of 6 O&M technicians and 3.5 crane operators - 3 days of work, including one day for mobilization and one day for demobilization <p>Total: 28.5</p> <p>The replacement of a generator requires 0.1295 FTE.</p> <p>Generator mass: 6.7 tonnes (Siemens Wind Power, 1999)</p> <p>Estimation #3²⁰ (shaft, not used)</p> <p>Replacement of a shaft</p> <ul style="list-style-type: none"> - Requires a team of 8 workers, 4 technicians, 2 ground supervisors, and 2 truck and crane operators - For 3 days, including one day for mobilization and one day for demobilization <p>Total: 24 man days</p> <p>The replacement of a shaft requires 0.109 FTE.</p> <p>Shaft mass: 7.6 tonnes (Siemens Wind Power, 1999)</p>

Activities	FTE ratio	Calculations
Replacement of a gearbox	0.136 per turbine	<p>Estimation #1²¹ (gearbox)</p> <p>Replacement of a Bonus 1.3 gearbox</p> <ul style="list-style-type: none"> - 6 days of project management and documentation - 1 site manager for 5 days - 3 technicians for 5 days - 4 days of mobilisation and demobilisation <p>Total: 30 man days</p> <p>The replacement of a gearbox requires 0.1364</p>
Decommissioning	0.314 per MW	<p>Estimation #1²²</p> <p>Dismantling 3 onshore turbines requires:</p> <ul style="list-style-type: none"> - 2 FTE for six months (240 days) for technical preparation - 7.5 FTE for three weeks (112.5 days) for the actual dismantling operation <p>Total: 352.5 man days for 3 turbines, 117.5 man days per turbine</p> <p>Number of FTE required to dismantle a single turbine: 0.534</p> <p>Onshore turbines typically have an average capacity of 1,7 MW (a total of 9,237 turbines generating 15,911.980 MW) (RenewableUK, 2025).</p> <p>Number of FTE: 0.314 per MW</p>

¹⁸ Interview of stakeholder 3_04.

¹⁹ Interview of stakeholder 3_03

²⁰ Interview of stakeholder 3_04.

²¹ Interview of stakeholder 3_04.

²² Interview of stakeholder 4_01

Activities	FTE ratio	Calculations
Part and turbine refurbishment	0.0188 per tonne	<p>Estimation #1</p> <p>Assumption: FTE per tonne for refurbishing onshore parts and turbines is the same as for refurbishing offshore parts and turbines.</p> <p>Estimation #2 (generator)²³</p> <p>Rewinding a main onshore generator: 1,500 hours</p> <p>Number of FTE: 0,852</p> <p>Generator mass: 6.7 tonnes (GE Power, 2015)</p> <p>Number of FTE per tonne: 0.127</p>
Material recovery (steel)	0.001 per tonne	<p>The UK metals recycling industry processes over 11.5 Mt of ferrous and non-ferrous metals each year (BMRA, 2025).</p> <p>The UK metals recycling industry currently directly employs over 15,000 people (BMRA, 2025).</p>
Material recovery (composite)	0.005 per tonne	A 75 FTE workforce is required to mechanically recycle 15,000 tonnes of waste annually (ADEME, 2015).
Material recovery (concrete)	0.0005 per tonne	0.47 FTE (direct and indirect) to recycle 1,000 tonnes of construction and demolition waste (EPA, 2020).

Table 74: Number of FTE ratio for offshore turbines

Activities	FTE ratio	Calculations
Operations & Maintenance	0.155 per MW	<p>Estimation #1 (Almqvist, 2023)</p> <p>0.155 FTE per MW</p>

²³ Interview of stakeholder 1_02

Activities	FTE ratio	Calculations
Replacement of a blade	0.0727 per replacement	<p>Estimation #1</p> <p>The replacement of a blade requires 0.0727</p> <ul style="list-style-type: none"> - 6 technicians working on the turbine - 2 technicians on the vessel (estimate) - Marine operations: 2 days (Avanessova, 2023) <p><i>0% UK FTE for offshore major replacement labour.</i></p>
Replacement of a gearbox	0 per replacement	<p>Estimation #1²⁴</p> <p>The replacement of a gearbox requires 0,1091 FTE.</p> <ul style="list-style-type: none"> - 6 technicians working on the turbine - 2 technicians on the vessel (estimate) - Marine operations: 3 days <p>A blade mass is 35 tonnes (estimate)</p> <p><i>The vessel crew (Spowind, 2025) is not considered (indirect jobs).</i></p> <p><i>0% UK FTE for offshore major replacement labour.</i></p> <p>Estimation #2²⁵</p> <p>The replacement of a major component requires:</p> <ul style="list-style-type: none"> - 5 to 6 technicians - 1 week (5 days) <p>The replacement of a part requires 0.125</p>

²⁴ Interview of stakeholder 4_02

²⁵ Interview of stakeholder 9_01

Activities	FTE ratio	Calculations
Replacement of a generator	0.1455 per replacement	Estimation #1 The replacement of a blade requires 0.1455 - 6 technicians working on the turbine - 2 technicians on the vessel (estimate) - Marine operations: 4 days (Avanessova, 2023) <i>0% UK FTE for offshore major replacement labour.</i>
Decommissioning	0.713 per MW	Estimation #1 (QBIS, 2020) 0,713 per MW Estimation #2 (Morgan Offshore Wind Ltd, 2024) Capacity: 100 x 15MW Direct FTE: 460 FTE per MW: 0.3067

Activities	FTE ratio	Calculations
Part and turbine refurbishment	0.0188 per tonne	<p>Estimation #1 (BVG Associates, 2023)</p> <p>Number of FTE: 2,209</p> <p>Mass: 11,731 tonnes (129,039 tonnes divided by 11 years)</p> <p>10% of reuse mass is assumed to be refurbished</p> <p>Number of FTE per tonne: 0.0188</p> <p>Estimation #2 (generator)²⁶</p> <p>Rewinding a main offshore generator: 1,500 hours</p> <p>Number of FTE: 0.852</p> <p>15 MW direct-drive generator mass: 300 tonnes (Gaertner et al., 2020)</p> <p>Number of FTE per tonne: 0.002</p>
Material recovery (steel)	0.001 per tonne	<i>See above.</i>
Material recovery (composites)	0,005 per tonne	<i>See above.</i>
Material recovery (concrete)	0.0005 per tonne	<i>See above.</i>

C.2 Economic modelling assumptions

There's a lack of data on the GVA, revenue, and net job impact of repair and recovery activities, sourced from academic publications, industry publications, and subject matter experts. To fill this data gap, several assumptions have been made, most of which significantly affect the estimation.

²⁶ Interview of stakeholder 1_02

C.2.1 General

The impacts on jobs and the GVA from repair and recovery activities for major part replacement, decommissioning, part refurbishment, and material recovery have been estimated.

The GVA of repair and recovery activities for onshore wind turbines has been assumed to be entirely sourced from the UK.

- This assumption may overestimate the GVA and number of FTE.

The GVA of repair and recovery activities for offshore wind turbines has been assumed to be 0% sourced from the UK for major parts replacements, 18% for decommissioning, 100% for turbine and part refurbishment and 100% for material recovery.

Major component replacement is assumed to be localised outside the UK (Pentland Floating Offshore Wind Farm, 2022). In addition, all wind turbine components, except for a few small component manufacturers, are manufactured outside the United Kingdom. Consequently, the manufacturing of new wind turbine components does not contribute to the GVA in the UK.

- When the local content is assumed to be 100%, the GVA and job impact are likely overestimated.

C.2.2 Operations & Maintenance

The impacts on jobs and GVA from O&M activities have been estimated for information only.

- O&M, with the exception of major parts replacement, has not been considered a repair and recovery activity.

C.2.3 Major parts replacement

The number of major part replacements only includes the replacement of blades, generators and gearbox.

- The impact of the replacement of other parts, such as nose cone, transformer and main shaft, has not been considered.
- Consequently, the number of jobs and GVA for major part replacement is likely significantly underestimated. For instance, the labour cost for replacing the main shaft or yaw ring of a turbine is higher than that for replacing a gearbox or generator.

The GVA and job impact for replacing major components of onshore turbines are based on a Bonus 1.3.

- A 1.3 MW is not fully representative of an average onshore turbine. 2.8 MW is the average turbine size (weighted by total installed capacity) and 1.8 MW average turbine size (weighted by total number of installed turbines).

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- The number of jobs required to replace a part of a turbine likely doesn't vary significantly based on the turbine's capacity. However, the cost of renting a crane along with the type and size of replacement part can vary significantly based on the turbine's capacity, which may affect the GVA.

The GVA and job impact of replacing major components of offshore turbines are based on limited data.

- These estimates don't consider the diverse sizes of offshore turbines.

The same number of FTE and GVA per replacement has been used for offshore gearbox, generator and blade replacement.

Major component replacement is assumed to be localised outside the UK (Pentland Floating Offshore Wind Farm, 2022).

- For example, jack-up vessels are predominantly owned and operated by non-UK companies.
- As a result, the UK GVA for major component replacements has been estimated to zero.

Vessels are used for two to four days per turbine to replace parts in offshore wind turbines.

- Some estimations provide a shorter time frame.

The weather standby days during onshore and offshore part replacement or decommissioning operations have not been considered.

- Weather-induced delays are a major cost factor accounting for 15-40% of the average removal costs (TNO, 2025).

Jobs performed by the vessel crew during a repair and recovery operation of an offshore wind turbine are considered indirect jobs.

C.2.4 Decommissioning

Since the estimation of offshore decommissioning costs per MW varies significantly, from £172,500/MW (TNO, 2025) to 482,000 (Adedipe et al., 2020), the GVA assessment for decommissioning is subject to significant uncertainty.

- The number of offshore wind developments that have undergone decommissioning to date is limited, therefore estimates of the costs and activities associated with decommissioning an offshore windfarm of this scale are based on projections, rather than experience.

C.2.5 Turbine and part refurbishment

All refurbished parts are refurbished in UK.

The FTE per tonne for refurbishing onshore parts and turbines is identical to that for offshore parts and turbines.

The FTE per tonne and GVA per tonne for recovering blades are comparable to those for gearboxes and generators.

- Consequently, the estimated number of FTE and GVA will likely be overstated.

C.2.6 Material recovery

Wind turbine blades are recycled exclusively through mechanical recycling, with no chemical recycling facilities currently available or planned.

Jobs creation, both direct and indirect, and GVA has been estimated to 0 for no material recovery and landfilling operations.

C.3 Economic modelling sensitivities

Table 75: Onshore jobs for each activity sensitivity analysis for a minimum and maximum replacement rate.

Scenario	Employment (job-years) (direct and indirect)			
	Turbines and parts refurbishment		Material recovery	
	Min	Max	Min	Max
BAU	13,700	17,400	10,600	11,800
Shorter	16,000	20,100	10,000	11,000
Longer	8,600	11,000	11,200	12,700

Table 76: Onshore GVA for each activity sensitivity analysis for a minimum and maximum replacement rate £million.

Scenario	GVA (£million) (direct and indirect)			
	Turbines and parts refurbishment		Material recovery	
	Min	Max	Min	Max
BAU	435	550	910	1,040

GVA (£million) (direct and indirect)				
Scenario	Turbines and parts refurbishment		Material recovery	
	Min	Max	Min	Max
Shorter	525	635	855	950
Longer	270	345	970	1,125

Table 77: Offshore employment (job-years) for each activity sensitivity analysis for a minimum and maximum replacement rate

Employment (job-years) (direct and indirect)				
Scenario	Turbines and parts refurbishment		Material recovery	
	Min	Max	Min	Max
BAU	15,800	22,500	21,300	25,000
Shorter	23,300	34,900	12,800	15,500
Longer	2,300	5,200	5,700	9,800

Table 78: Offshore GVA for each activity sensitivity analysis for a minimum and maximum replacement rate

GVA (£million) (direct and indirect)				
Scenario	Turbines and parts refurbishment		Material recovery	
	Min	Max	Min	Max
BAU	335	480	2,205	2,575
Shorter	500	745	1,325	1,590

Scenario	GVA (£million) (direct and indirect)			
	Turbines and parts refurbishment		Material recovery	
	Min	Max	Min	Max
Longer	50	110	565	975

Table 79: Onshore changing ratios of second-hand for steel, iron and composites employment impacts

Sensitivity parameter	Employment (job-years) (direct and indirect)					
	Turbines and parts refurbishment			Material recovery		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Baseline	14,900	17,700	9,300	11,000	10,300	11,700
Second lifecycle fraction -10%	7,800	10,900	2,200	11,800	11,000	12,500
Second lifecycle fraction +10%	22,000	24,500	16,500	10,200	9,600	10,900
Second lifecycle fraction +20%	29,000	31,300	23,700	9,400	8,800	10,100

Table 80: Offshore changing ratios of second-hand for steel, iron and composites employment impacts

Sensitivity parameter	Employment (job-years) (direct and indirect)					
	Turbines and parts refurbishment			Material recovery		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Baseline	17,700	27,500	15,000	22,600	21,400	23,200
Second lifecycle fraction - 10%	3,000	13,000	0	23,800	22,600	24,500
Second lifecycle fraction +10%	32,500	42,000	30,100	21,400	20,300	22,000
Second lifecycle fraction +20%	47,300	56,400	45,200	20,200	19,000	20,800

Table 81: Onshore changing ratios of second-hand for steel, iron and composites GVA

Sensitivity parameter	GVA (£million) (direct and indirect)					
	Turbines and parts refurbishment			Material recovery		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Baseline	470	560	295	950	885	1,020
Second lifecycle fraction - 10%	250	345	70	1,030	960	1,100

Sensitivity parameter	GVA (£million) (direct and indirect)					
	Turbines and parts refurbishment			Material recovery		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Second lifecycle fraction +10%	695	775	520	875	810	945
Second lifecycle fraction +20%	920	990	750	795	735	865

Table 82: Offshore changing ratios of second-hand for steel, iron and composites - GVA

Sensitivity parameter	GVA (£million) (direct and indirect)					
	Turbines and parts refurbishment			Material recovery		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Baseline	375	585	320	2,325	2,215	2,380
Second lifecycle fraction - 10%	65	280	0	2,440	2,325	2,500
Second lifecycle fraction +10%	695	895	645	2,210	2,105	2,260
Second lifecycle fraction +20%	1,010	1,205	965	2,100	1,990	2,145

Table 83: Onshore and offshore wind variation of recovery/no recovery fraction of blade composites - employment

Sensitivity parameter	Employment (job-years) (direct and indirect)- Material Recovery total					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
100% recovery composites	12,300	11,500	13,200	25,500	23,900	26,400
75% recovery composites	11,700	10,900	12,500	24,000	22,600	24,800
25% recovery composites	10,300	9,700	10,900	21,200	20,200	21,600
0% recovery composites	9,600	9,147	10,200	19,700	19,000	20,000

Table 84: Onshore and offshore wind variation of recovery/no recovery fraction of blade composites - GVA

Sensitivity parameter	GVA (£million) (direct and indirect)- Material Recovery total					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
100% recovery composites	1,045	965	1,130	2,530	2,385	2,605

Sensitivity parameter	GVA (£million) (direct and indirect)- Material Recovery total					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
75% recovery composites	1,000	925	1,075	2,425	2,300	2,495
25% recovery composites	900	845	970	2,225	2,130	2,270
0% recovery composites	855	800	915	2,125	2,045	2,160

Table 85: Onshore and offshore wind variation of recovery/no recovery fraction of steel and iron – jobs.

Sensitivity parameter	Employment (job-years) (direct and indirect)- Material Recovery total					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
75% recovery steel and iron	10,000	9,400	10,600	18,500	17,500	19,000
50% recovery steel and iron	8,700	8,300	9,200	13,300	12,400	13,700
25% recovery steel and iron	7,500	7,100	7,800	8,000	7,500	8,500

Sensitivity parameter	Employment (job-years) (direct and indirect)- Material Recovery total					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
5% recovery steel and iron	6,400	6,200	6,600	4,000	3,500	4,300

Table 86: Onshore and offshore wind variation of recovery/no recovery fraction of steel and iron – GVA

Sensitivity parameter	GVA (£million) (direct and indirect)- Material Recovery					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
75% recovery steel and iron	840	785	900	1,880	1,785	1,930
50% recovery steel and iron	705	665	750	1,320	1,250	1,360
25% recovery steel and iron	570	540	600	760	710	790
5% recovery steel and iron	460	445	745	315	280	340

Table 87: Onshore and offshore wind variation of recovery/no recovery fraction of concrete – jobs

Sensitivity parameter	Employment (job-years) (direct and indirect)- Material Recovery					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
100% recovery concrete	15,800	15,100	16,500	-	-	-
75% recovery concrete	13,400	12,700	14,100	-	-	-
25% recovery concrete	8,600	7,900	9,300	-	-	-
0% recovery concrete	6,200	5,500	6,900	-	-	-

Table 88: Onshore and offshore wind variation of recovery/no recovery fraction of concrete – GVA

Sensitivity parameter	GVA (£million) (direct and indirect)- Material Recovery					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
100% recovery concrete	1,290	1,225	1,360	-	-	-
75% recovery concrete	1,120	1,055	1,190	-	-	-

Sensitivity parameter	GVA (£million) (direct and indirect)- Material Recovery					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
25% recovery concrete	780	715	855	-	-	-
0% recovery concrete	615	545	685	-	-	-

Appendix D: Emissions impact assessment

D.1 Emissions modelling emission factors

Table 89: Emission factors used for materials, operations, decommissioning and transport lifecycle phases.

Parameter	Value	Units
Low alloyed steel (Ecoinvent, 2025) ²⁷	-	kgCO2e/kg
Steel - metal working (Ecoinvent, 2025)	-	kgCO2e/kg
Cast iron (Ecoinvent, 2025)	-	kgCO2e/kg
Glass fibre reinforced plastic (Ecoinvent, 2025)	-	kgCO2e/kg
Carbon fibre reinforced plastic (Ecoinvent, 2025)	-	kgCO2e/kg
Concrete (Oekobaudat, 2022)	0.122	kgCO2e/kg
Crawler crane - lifting operations (Liebherr, 2024)	0.671	kgCO2e/kWh
Diesel (DESNZ, 2025)	2.662	kgCO2e/litre
Marine Fuel Oil (DESNZ, 2025)	3.102	kgCO2e/litre

²⁷ License required to access emission factor Ecoinvent values.

Parameter	Value	Units
Generic waste processing (IStructE, 2020)	0.013	kgCO2e/kg
Steel EoL material processing (Ecoinvent, 2025)	-	kgCO2e/kg
Transport - freight truck (Ecoinvent, 2025)	-	kgCO2e/tonne*km
Transport - freight shipping (Ecoinvent, 2025)	-	kgCO2e/tonne*km
Transport - freight train (Ecoinvent, 2025)	-	kgCO2e/tonne*km
Concrete processing (Oekobaumat, 2022)	0.0068	kgCO2e/kg
Concrete recycling credit (Oekobaumat, 2022)	-0.007	kgCO2e/kg
Composite mechanical recycling (Bennet et al., 2021)	0.121	kgCO2e/kg
Composite recycling credit (Oekobaumat, 2022)	-0.007	kgCO2e/kg
Steel processing – BOF (Worldsteel, 2025)	2.32	kgCO2e/kg
Steel processing – EAF (Worldsteel, 2025)	0.7	kgCO2e/kg
Concrete landfill (DESNZ, 2025)	0.0013	kgCO2e/kg
Scrap steel landfill (DESNZ, 2025)	0.009	kgCO2e/kg
Composite landfill (DESNZ, 2025)	0.009	kgCO2e/kg

D.2 Emissions modelling assumptions

Table 90: Onshore and offshore wind materials, operations, decommissioning and transport assumptions.

Parameter	Assumption
Net capacity factors	<ul style="list-style-type: none"> - Offshore wind – 38.14% (RenewableUK, 2025) - Onshore wind – 25.34% (RenewableUK, 2025)
Blade composite material breakdown	Composite mass is broken down into 20% CFRP and 80% GFRP
Manufacturing emissions	Manufacturing emissions for concrete and composite material is included within the emission factor

Parameter	Assumption
Steel and iron material breakdown	Steel is 99% of the steel and iron mass total Iron is 1% of the steel and iron mass total
Onshore crane	24 hours of crane usage per turbine during onshore decommissioning (WindpowerNL, 2021) 12 hours of crane usage per component during onshore major component replacement (Windpower Monthly, 2016)
Offshore vessel	48 hours of vessel usage per component during major component replacement 96 hours of vessel usage per turbine during offshore decommissioning
Onshore crane engine	Crawler crane usage to complete onshore turbine lifting operations - 230kW diesel engine (Liebherr, 2022).
Offshore vessel fuel consumption	Medium jack-up vessel uses 1,200 litres of marine fuel oil per hour during operation
Concrete density	C35 concrete density of 2400kg per m3 (Oekobaudat, 2022)
Excavator removal rate	Excavator reinforced concrete removal rate per hour of 26.3m3 (Methvin, 2025) Excavator fuel rate of 11 litres per hour (Liebherr, 2022)
Turbine materials	Steel, iron and composite materials are 90% of the total turbine materials (Vestas, 2024)
Offshore transit time	Transit time from O&M port to site is not considered
Transport – UK steel, iron and composite	Steel, iron and composite material transport distance within the UK is 200km (Vestas, 2024)
Transport – UK concrete	Concrete material transport distance within the UK is 50km (Vestas, 2024)
Transport – steel processing	Steel material processing - UK port (Hull) to Rotterdam is 350km
Transport – steel processing	Steel material processing - Rotterdam to processing facility is 100km by train

Parameter	Assumption
Transport – steel processing	Steel material processing - Rotterdam to processing facility is 50km by truck
Reuse – steel	Steel second lifecycle material quality retained 95%
Recovery – steel	Steel material recovery – All steel sent to an electric arc furnace in the EU for the baseline scenario
Recovery – steel	Steel material recovery – Electric arc furnace with 90% material quality retained (BCSA, 2022)
Recovery – steel	Steel material recovery – Basic oxygen furnace with 90% material quality retained (BCSA, 2022)
No recovery – steel	Steel no material recovery – 100% to landfill
Reuse – concrete	Concrete has no second lifecycle
Recovery – concrete	Concrete material recovery - 100% used as construction aggregate filler
No recovery – concrete	Concrete no material recovery - 100% to landfill
Reuse – composite	Composite second lifecycle material quality retained 90%
Recovery – composite	Composite material recovery - 100% used as construction aggregate filler
No recovery – composite	Composite no material recovery - 50% to landfill
No recovery – composite	Composite no material recovery - 50% to incineration with energy recovery

D.3 Emissions modelling sensitivities

Table 91: Onshore and offshore wind variation of recovery/no recovery fraction of blade composites - tonnes CO₂e per GWh (1990 – 2070).

Sensitivity parameter	Tonnes CO ₂ e per GWh					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
100% recovery composites	15.83	18.83	14.76	16.75	18.99	14.93
75% recovery composites	15.83	18.83	14.76	16.74	18.99	14.92
25% recovery composites	15.81	18.81	14.74	16.73	18.97	14.91
0% recovery composites	15.81	18.81	14.73	16.72	18.97	14.90

Table 92: Onshore and offshore wind variation of recovery/no recovery fraction of steel and iron - tonnes CO₂e per GWh (1990 – 2070).

Sensitivity parameter	Tonnes CO ₂ e per GWh					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
75% recovery steel and iron	16.46	19.71	15.12	17.79	20.19	15.83
50% recovery steel and iron	17.10	20.38	15.89	19.10	21.70	16.97
25% recovery steel and iron	17.73	21.06	16.66	20.41	23.22	18.11

Sensitivity parameter	Tonnes CO ₂ e per GWh					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
5% recovery steel and iron	18.24	21.60	17.27	21.46	24.43	19.03

Table 93: Onshore and offshore wind variation of recovery/no recovery fraction of concrete - tonnes CO₂e per GWh (1990 – 2070).

Sensitivity parameter	Tonnes CO ₂ e per GWh					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
100% recovery concrete	15.81	18.81	14.74	-	-	-
75% recovery concrete	15.82	18.82	14.74	-	-	-
25% recovery concrete	15.82	18.83	14.75	-	-	-
0% recovery concrete	15.83	18.83	14.75	-	-	-

Table 94: Onshore and offshore changing ratios of second-hand for steel, iron and composites - tonnes CO₂e per GWh (1990 – 2070).

Sensitivity parameter	Tonnes CO ₂ e per GWh					
	Onshore			Offshore		
	BAU	Shorter Lifetime	Longer Lifetime	BAU	Shorter Lifetime	Longer Lifetime
Second lifecycle fraction -10%	16.54	19.67	15.44	17.32	19.63	15.45
Baseline	15.82	18.82	15.65	16.74	18.98	14.92
Second lifecycle fraction +10%	15.10	17.97	14.05	16.16	18.33	14.38
Second lifecycle fraction +20%	14.38	17.12	13.36	15.57	17.67	13.85

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