BVGAssociates

Circularity market analysis

Assessing the potential market size and economic benefits in the UK of moving toward a circular model for operational wind turbine components

March 2023

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Executive summary

There is a significant commercial opportunity to establish a circular supply chain in the UK for the wind industry. This opportunity is supported by a large home market with a relatively secure future and is boosted by a significant European export opportunity, which provides an opportunity of at least six times that of the UK market.

By 2035 there will be approximately 584 GW of operational wind capacity across the 10 countries covered in this study, provided by around 120,000 turbines. Based on just ten components with significant reuse, refurbishment and remanufacturing potential, we estimate the size of the potential benefits to the UK economy from building supply chain capabilities to be around £1.6 billion in total Gross Value Added (GVA) for the period between 2025 and 2035, based on UK demand only. This increases to around £9.6 billion when expanded to include the nine further European markets, which has the potential to support 20,111 full-time equivalent jobs in the UK by 2035.

Measuring environmental impact using the metric “avoided waste to scrap”, we estimate that 806,978 tonnes of waste to scrap could be avoided from 2025 to 2035, with most of this coming from the onshore turbines in the 1 to 5 MW class.

These figures include only those parts refurbished during their operational life. The analysis does not consider the substantial opportunity that is created by turbine decommissioning.

The timing is right for the UK to become a major player and front-runner in the nascent wind turbine component circularity market, due to:

- Strong local and export markets
- Limited competition at present
- Indigenous supply chain already in development
- Strong alignment with significant government policies at Scottish, UK and EU level, and
- Currently being ahead of the underlying political and social pressures providing the chance to proactively shape and lead the available opportunity, rather than be led by them.

While we observe a general alignment of policies on circularity at all levels, we acknowledge that legal and regulatory obligations on the wind industry are currently very limited. Without these obligations there is a risk that the industry feels a lack of urgency to enact change. If the UK wind industry is to maximise the potential of this market, we would encourage a proactive industry wide approach that embraces change. The window of opportunity will close as industry in general catches up with the wider political and social landscape, and we expect circularity to become a commercial imperative in the foreseeable future. The early adopter advantage will be lost if the UK is not proactive in terms of developing the opportunity.

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1. Introduction

SSE Renewables (SSER) is working with University of Strathclyde (UoS) and Renewable Parts (RPL) to progress the case for circularity in wind energy as a major economic opportunity, and is seeking to bring together the sector to join forces and unlock this economic potential. This report by BVG Associates (BVGA) was commissioned by SSER to support this ongoing initiative.

This report presents:

- A general narrative on the regulatory and commercial drivers towards circularity
- An overview of circularity in other industries
- A high-level commentary on the skills and capability requirements to bridge the gap between the potential market and the current status quo
- A high-level assessment of the total potential market for wind turbine reuse, refurbishment and remanufacturing of ten component parts between 2025 and 2035 for the top 10 (by installed wind capacity) coastal countries in north and west Europe, and
- Quantification of the potential economic contribution to the UK from this market, measured in terms of Gross Value Added (GVA) and full-time equivalent (FTE) jobs supported.

2. Regulatory and commercial drivers

2.1. Circular economy principles

The principles of a circular economy are based on the idea of keeping materials and resources in use for as long as possible, reducing waste and pollution, and regenerating natural systems. There is not an accepted universal definition of what these principles are – different organisations place different emphasis on different areas, depending on their focus. Our summary of these principles is as follows:

- **Design for durability and recyclability**: Products and materials should be designed with a focus on durability, repairability, and recyclability, so that they can be used for as long as possible.
- **Embrace the value of waste**: Waste should be seen as a valuable resource, and efforts should be made to recover and reuse materials wherever possible. This can include recycling, repurposing, and reusing materials to create new products.
- **Preserve and enhance natural systems**: Natural systems, including ecosystems and biodiversity, should be preserved and enhanced through circular economy practices. This can involve regenerative agriculture, sustainable forestry, and other practices that support the health and resilience of natural systems.
- **Use renewable energy**: The circular economy should rely on renewable energy sources, such as solar and wind power, to reduce the carbon footprint of economic activity.
- **Foster collaboration and partnerships**: Collaboration and partnerships between businesses, governments, and civil society organisations are essential for the transition to a circular economy. This can involve sharing knowledge, resources, and best practices to support the development of circular business models and systems.

2.2. Policy drivers

The political dynamics behind a circular economy can be complex, combining the interest of both heavy industry and environmental concerns to both use resources more efficiently and reduce environmental impact of this use.

Much of the published policy and legislation around the issue of a circular economy deals with consumer goods, addressing waste streams, planned obsolesce and repairability. While related and of some general relevance, these policy documents do not relate directly to the wind industry.

There are several key policies at EU, UK and Scotland level which are driving the progress of a circular economy. Here we discuss those with the most relevance to the work presented in this report.

2.2.1 EU level policy

Several EU policy documents reference circularity, with a predominant focus on consumer goods and waste:

- **The Waste Framework Directive** addresses extended producer responsibility deals with Waste Electrical and Electronic Equipment (WEEE). [i]
- **The Eco-design Directive** further targets consumer goods, mandating minimum efficiency levels and energy consumption labelling. [ii]
- **The circular economy action plan** (CEAP), adopted in March 2020 is a key component of the European Green Deal, and while it maintains a focus on consumer goods, it makes direct reference to circularity of materials in manufacturing and construction, but does not provide direct recommendations or guidance. [iii] This is in its second edition, which has a greater focus on design and production than the first, which

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[i] https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

[ii] https://single-market-economy.ec.europa.eu/single-market/european-standards/harmonised-standards/ecodesign_en

[iii] https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

focussed on waste and recycling. Through 2022 there were a range of proposal adopted which added focus on product-related circularity measures.

- **Horizon**, a large European Union funded research program, has allocated 180 million euros to research circular economy in its 2023 funding round. [iv]

It is worth noting that there is a call to ban wind turbine blades from going to landfill, and upcoming legislation on the management of critical raw materials.[v,vi] These will directly affect the wind industry if/when they enter into legislation.

2.2.2 UK level policy

- **Circular economy package** introduced in 2020. Identifies steps for the reduction of waste and establishes a long-term path for waste management and recycling. Relatively small technical changes to existing legislation which does not specifically mention manufacturing. Focus is on encouraging better waste management and to reduce waste. [vii]
- **Circular economy centres** five circular economy centres were announced in 2020, with £22.5 million of government investment. [viii] They have been setup to explore reusing waste materials in the textiles, construction, chemical and metal industries with a focus on economic benefit potential. Construction and manufacturing centres focus on mineral-based construction materials, chemicals, and metals. Operated by UKRI, the focus of these centres is innovation and research.
- **Industrial decarbonisation strategy** covers circular economy opportunity in more detail within industry, emphasizing a strategy of support increasing reuse, repair, and remanufacturing. [ix] Tangible policy support for circular economy within industry is not offered beyond a £30 million UKRI research pot.

2.2.3 Scottish level policy

Waste policy is devolved to the Scottish Government and therefore separate circular economy policy applies. Notably, the circular economy in Scotland is specifically covered in a ministerial role, with Lorna Slater (Green MSP) in post as Scotland's green skills, circular economy and biodiversity minister. There is no circular economy minister in Westminster.

- **Making Things Last: a circular economy strategy for Scotland** was published in 2016 and made explicit reference to energy infrastructure, construction, and industry. [x] The document states "*there are considerable opportunities such as the reuse of equipment from wind turbines and decommissioned oil and gas platforms*." While this is the only explicit reference to wind turbines in any examined policy documents, it does not offer any further details.
- **A Circular Economy Bill**, a parliamentary bill expanding on the *Making Things Last* document consulted on in Scotland in 2022 and expected to be published in 2023. [xi]
- **Energy Strategy and Just Transition Plan** is currently in the consultation period until May 2023. It explicitly highlights circular economy principles in reference to the wind industry, stating "*We support the use of recycled and refurbished turbines, recognising the enormous potential to strengthen the Scottish supply*

[iv] https://hadea.ec.europa.eu/calls-proposals/horizon-europe-calls-2023-destination-1-climate-neutral-circular-and-digitised-production_en

[v] https://windeurope.org/wp-content/uploads/files/policy/position-papers/WindEurope-position-paper-how-to-build-a-circular-economy.pdf

[vi] https://single-market-economy.ec.europa.eu/publications/european-critical-raw-materials-act_en

[vii] https://www.gov.uk/government/publications/circular-economy-package-policy-statement

[viii] https://ce-hub.org/ce-centres/

[ix] https://www.gov.uk/government/publications/industrial-decarbonisation-strategy

[x] https://www.gov.scot/publications/making-things-last-circular-economy-strategy-scotland/

[xi] https://www.gov.scot/publications/delivering-scotlands-circular-economy-consultation-proposals-circular-economy-bill/pages/4/

chain, reduce waste, utilise more of our local skills and capabilities and improve costs for the onshore wind sector.”.[xii]

- **The Scottish Government’s Onshore Wind Policy Statement 2022** sets out a wide agenda supporting the ambition of 20 GW of operational wind in Scotland by 2030.[xiii] Of particular relevance to this report is Chapter 5 and specifically Chapters 5.2 to 5.4 which discuss the ambitions for the supply chain, repowering and enhancing the circular economy within the wind industry.

> We recognise that, at present, the Scottish manufacturing supply chain for the wind industry is weak. Over the coming years we have a real opportunity to create an established remanufacturing industry based on circular economy principles. This has the potential to add significant investment into Scotland's economy, as well as introduce new skills and support new direct, and indirect, jobs to meet increasing demand. Additionally, a local supply chain of remanufactured components reduces the reliance on the global supply chain and could reduce the lead time of the construction phase of wind energy development.

Chapter 5.2.3 of the Onshore Wind policy Statement 2022

- **Resource Efficient Scotland** is a Scottish government funded programme, set up to offer free advice and technical support to businesses, the public and the third sector, as well as the sharing of best practices and new technologies. It is focussed on saving money through efficiency.[xiv]
- **Zero Waste Scotland** is a company funded by the Scottish Government and receives funding from the EU’s European Structural and Investment Funds. Its goal is to make Scotland a pioneer of the circular economy.[xv] It focuses on responsible consumption from people and businesses, responsible production, and maximising value from waste.

2.3. Economic and commercial drivers

A circular economy presents a range of economic and commercial opportunities for businesses, including:

- Resource scarcity: As natural resources become scarcer and more expensive to extract, it becomes increasingly important to use them more efficiently and reduce waste. By adopting circular economy practices, businesses can reduce their reliance on finite resources and develop more sustainable supply chains.
- Job creation: The circular economy can also create new job opportunities in areas such as waste management, product design, and repair and refurbishment services. This can provide economic benefits for local communities and contribute to sustainable economic growth.
- Cost savings: By reducing waste, increasing resource efficiency, and extending the lifespan of products, businesses can save money on materials, energy, and waste disposal costs.
- New revenue streams: The circular economy can create new revenue streams for businesses, such as by selling recycled materials, refurbishing products, or providing repair services.

[xii] https://www.gov.scot/publications/draft-energy-strategy-transition-plan/

[xiii] https://www.gov.scot/publications/onshore-wind-policy-statement-2022/pages/6/

[xiv] https://www.gov.scot/policies/managing-waste/resource-efficiency/

[xv] https://www.zerowastescotland.org.uk/

- Competitive advantage: Companies that adopt circular economy practices can gain a competitive advantage by reducing their environmental impact, improving their reputation, and meeting the growing demand for sustainable products and services.
- Innovation: The circular economy requires new approaches to product design, business models, and supply chain management, creating opportunities for innovation and differentiation.
- Access to new markets: The circular economy can open up new markets for businesses, such as by providing access to customers who are looking for sustainable products and services.
- Improved stakeholder relations: The circular economy can help businesses build stronger relationships with stakeholders, such as customers, suppliers, and investors, by demonstrating their commitment to sustainability and corporate responsibility.

Overall, a circular economy presents a range of opportunities for businesses that are willing to adopt sustainable practices and embrace the principles of the circular economy. By reducing waste, increasing resource efficiency, and adopting innovative approaches to product design and business models, companies can improve their bottom line, while also contributing to a more sustainable and resilient economy.

2.4. Relevance to the UK's wind industry

The agenda of circularity and zero-waste is well advanced in terms of the overall EU and UK political agenda. It has developed considerable momentum across the political spectrum and is firmly embedded in the policy and regulatory landscape. The different levels of policy in the EU, UK and Scotland are already well aligned on the issues and overall direction of travel, although the legislation that does exist is relatively high level and it is likely that policy will evolve and become more far reaching and impactful in terms of obligations on industry and the supply-chain.

Although there is little in the current legislation which directly targets the wind industry, we believe that there is a momentum behind zero waste and circular policies which makes it likely that tighter regulation is coming, either from EU, UK or Scottish Government levels. We recognise that EU legislation does not necessarily apply directly at UK or Scottish levels, however it will apply to EU-based parts of the wind energy supply chain.

The challenge for the UK's wind industry is in overcoming what has been lack of political, and hence internal, urgency. Until recently, the EU and national policies have not reached down into the details of industrial strategies. With the recent release of the Scottish Government's Energy and Just Transition Strategy, however, this has changed, and there is now a clear expectation from Scottish Government of the wind industry to increase circularity and reduce waste.[xii]

> Adopting a circular economy approach to sourcing materials for renewable energy developments both safeguards against potential future resource shortages and reduces the greenhouse gas emissions involved in manufacturing and transportation. We support the use of recycled and refurbished turbines, recognising the enormous potential to strengthen the Scottish supply chain, reduce waste, utilise more of our local skills and capabilities and improve costs for the onshore wind sector.

Extract from the draft Energy and Just Transition Strategy

Although this does not commit the wind industry to anything specific or place legal obligation on suppliers or operators, the political intent is clear. We expect this principle will be brought into focus when the Scottish Onshore Wind Sector Deal is released.[xvi] The sector deal will itemise specific agreements between industry and government with the aim of delivering at least 20 GW of operational onshore wind by 2030. While the details

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[xvi] Reference here! Expected to be released in Autumn 2023

have yet to be determined, the published sector deal vision statement commits to a focus on circularity and zero waste ambitions.

We recognise that strategy white papers and sector deals do not necessarily form legally binding obligations on industry and that a robust regulatory framework is required to forcibly drive change. The UK’s wind industry, which is mostly concentrated in Scotland, nevertheless can take a proactive approach to implementing a circular economy agenda, prioritising cross-industry collaboration and innovation in order to maximise environmental and economic impact and to stay ahead of the likely increase in political and regulatory pressure.

3. Experience from other industries

In this section we present the experience of developing circular economies in other industries.

3.1. Aviation

In the wake of political and consumer pressure to reduce the climate impacts associated with flying, the aviation industry has adopted circular economy principles to reduce its environmental footprint. A variety of measures have been implemented across all elements of the aviation sector, but perhaps most relevant to the wind industry are the steps taken to lower the throughput of energy and materials required to produce and maintain electrical equipment, mechanical equipment, and aircraft body parts.

Equipment end-of-life is a particular challenge for the aviation industry due to size of the operational aircraft fleet. The Aircraft Fleet Recycling Association (AFRA) estimates that 15,000 aircraft will retire in the next two decades.[xvii, xviii]

3.1.1 What has been done?

Aircraft suppliers are increasingly designing for circularity in their systems and parts. This means ensuring that aircraft can be easily dismantled for repair, refurbishment, and recycling. Improvements in aircraft dismantling and recycling have been led by AFRA which sets standards and targets for circularity and works with regulators and stakeholders to promote safe and sustainable practices. It also trains and accredits supply chain companies involved in the disassembly and recycling of aircraft.

Retired aircraft are selectively dismantled. Parts that cannot be reused are recycled. Current industry practice is that 90% of an aircraft's weight is reused or recycled following its service life in both aviation and non-aviation uses, with the remaining 10% going to landfill.

When an aircraft is dismantled, its parts are stripped before the fuselage is broken up for recycling. Aircraft suppliers such as Boeing and Airbus collect used serviceable parts from the field and recertify them for use. The suppliers catalogue these components and have created a large secondary marketplace for refurbished parts for their own fleets. This has reduced the lead times and costs associated with repairing in-service craft.

A single dismantled plane can provide up to 6,000 refurbished parts. These tend to be the higher value parts such as landing gear and avionics. Safety concerns have historically made it difficult to refurbish structural and mechanical parts. As such, most of the material used in a commercial civilian aircraft, which typically contains over 2 million parts, is recycled rather than reused.[xix]

Additive manufacturing is a promising technology that has the potential to enable structural and mechanical parts to be repaired more easily. In some cases, this may enable the fatigue life of parts to be reset by removing layers of material and recreating them with additive technology to remove fatigue initiation sites.

This has already been demonstrated for some Rolls Royce and Pratt and Whitney engine parts, with French digital printing outfit BeAM repairing 800 aerospace parts using 3D printers in 2015. Additive manufacturing can also be used to produce individual parts more efficiently, but its application within the aviation industry is limited by a lack of 3D printing technology and the challenges associated with certifying and qualifying parts, processes, and machinery.[xx]

[xvii] Aircraft Fleet Recycling Association, Washington DC, 2023, https://afraassociation.org/

[xviii] a non-profit trade body of 40 industry members that was established in 2006 to improve the end-of-life management of aircraft

[xix] Boeing, 'Sustainability is built in', Virginia, 2021 https://www.boeing.com/features/innovation-quarterly/2021/04/boeing-product-sustainability.page

[xx] Atkins, 'A circular economy for civil aerospace', 2021, available online at: https://www.snclavalin.com/~/media/Files/S/SNC-Lavalin/documents/circular-economy-in-aerospace-web3.pdf

There is a keen focus on increasing circularity in aviation, with the industry currently targeting the ability to recycle or reuse 95% of an aircraft's weight. Reaching this 95% target is the subject of ongoing R&D efforts such as Boeing's 'ecoDemonstrator' project where over 200 technologies have been tested in collaboration with industry partners. Eight different aircraft have served as flying test beds since the programme launched in 2012.[xxi] A recent innovation deployed on ecoDemonstrator was a carbon composite cabin interior sidewall made from fuselage production scrap. The sidewalls are lighter than traditional sidewalls and reduce cabin noise. This innovation provides benefits on several counts including reuse of waste to create a lighter, more energy efficient interior and is an excellent demonstration of consumer awareness driving political will, leading to investment and collaboration which in turn creates commercially attractive innovation.

3.2. Oil and gas

The oil and gas industry is under political and social pressure to improve its environmental performance. The industry has responded to this with the implementation of numerous measures to increase circularity in both upstream and downstream activities.

To usefully constrain the discussion to the elements most relevant to the offshore wind industry we will look at how the oil and gas industry has attempted to improve the circularity of components and infrastructure used during upstream extraction operations in the UK North Sea.

3.2.1 What has been done?

Oilfield equipment is complex and often bespoke, making the repair and refurbishment of parts at operational projects desirable and cost effective. This work is typically carried out in certified shops and covers a wide range of equipment from engine parts, pumps, compressors, rotor shafts, hydraulic equipment and pipes. Increasing circularity at the end of asset life is important as almost all recovered material from retired offshore oil and gas platforms in the UK is recycled, with very little re-used. There is however a larger market for refurbished parts in the US, the value of which was estimated to stand over more than $7.7 billion in 2011.[xxii]

Zero Waste Scotland, the Renaissance Society of America and Innovate UK led a project to improve the circularity during the decommissioning of UK Continental Shelf assets in 2015, due to an increase in planned asset retirements. This project reviewed existing literature, engaged with industry stakeholders, and developed reuse propositions for retired equipment, with a view to increasing the market for refurbished parts.

Some recent examples of circularity from North Sea operators' retirement processes include using jacket sections to build quays, selling cranes and booms, reuse of gas turbines for training purposes and conversion of offshore accommodation blocks into onshore office space. The most successful area of growth has been the market for decommissioned piping which can be used for a variety of construction purposes. There are several Scottish companies specialised in the processing of this material. Some 15 miles of recovered North Sea piping were used to build the Aberdeen Conference and Exhibition Centre in 2018.[xxiii]

Despite this, reuse and refurbishment still account for less than 2% of the overall weight of recovered material from decommissioned assets. The industry is still working to improve the business case for used and refurbished parts and equipment. This is an area of renewed focus within the oil and gas industry as shifting geopolitical factors make new leasing in the North Sea likely, with many credible voices forecasting a decade of higher energy prices ahead.

[xxi] Boeing, 'Accelerating innovation for a sustainable future' Virginia', 2022, https://www.boeing.com/principles/environment/ecodemonstrator

[xxii] RSA and Zero Waste Scotland, ' North Sea oil and gas rig decommissioning & Re-use opportunity report', 2016, available online at: https://www.thersa.org/globalassets/pdfs/reports/rsa-great-recovery---north-sea-oil-and-gas-report.pdf

[xxiii] Marques et al. 2021, 'Reusing and recycling decommissioned materials: is the glass half full or half empty', 2021, available online at: https://pure.hw.ac.uk/ws/portalfiles/portal/44258280/Decommissioning_Report_22.01.21.pdf

Recent industry sponsored research has highlighted several barriers preventing higher reuse rates including lack of demand for many types of used parts, lack of collaboration and information sharing ahead of decommissioning, and a lack of regulatory incentives promoting circularity.

3.3. Relevance to the UK's Wind Industry

The main takeaways from the aviation industry are:

- AFRA has played an important role in increasing the sustainability of the aviation industry. The organisation provides a platform for knowledge sharing between different industry stakeholders and ensures that the largest producers of parts are involved in their end-of-life management. No such organisation currently exists in the wind industry.
- Boeing's ecoDemonstrator is a positive example of large aviation OEMs providing a space for the live demonstration of circular economy principle in conjunction with industry partners, this helps quickly improve the technology readiness level (TRL) of promising technologies.
- Additive manufacturing is a high potential technology for increasing circularity and is currently being explored by turbine OEMs. There are likely to be cross sector learnings from the aviation industry that has been using this technology for several years already.

The main takeaways from the oil and gas industry are:

- A market for through-life repair and refurbishment of parts broadly exists within the oil and gas industry, but this is largely due to the bespoke design of many oil and gas assets.
- End-of-life circularity is a challenge, but experiences in the US and UK show that it is possible to achieve refurbishment and re-use of parts and machinery, but that many of these parts are still not reused within the oil and gas industry.
- Higher circularity for parts within the industry is unlikely to happen organically and improving this will require large scale collaboration between industry groups, supply chain companies, and regulators.

The comparison between the relative successes of the two industries is quite informative. Aviation has been demonstrably better at embracing the challenge of circularity, not just in achieving significant gains but also making it commercially attractive. While the success of AFRA appears to have been a significant differentiator, both industries have faced similar political pressure and similar technical barriers. Arguably aviation has been more successful because the industry has embraced the challenge and developed a collective will to find solutions.

The danger for the UK's wind industry is complacency. It should not let the increasing need for renewable energy be the end point of our journey but instead should embrace the challenge of circularity and turn it to its advantage, not just socially and politically, but commercially too.

3.4. Wind turbine blades

As a sector that champions the fight against climate change, the wind industry has been seeking ways to make its life cycle more circular, driven by an increasing global emphasis on sustainability and resource efficiency.

Many components of a wind turbine, such as the tower and nacelle have established recycling practices, with steel and aluminium being sent to foundries or steelworks and re-entering the materials chain. However, a component that is particularly difficult to recycle is the turbine blade, due to their composite nature which is typically made up of glass and carbon fibres and epoxy resins. Blade waste has historically ended up in landfills or incinerators and is the most glaring contradiction to a circular economy to be found within the wind sector.

3.4.1 What has been done?

Recent breakthroughs in manufacturing and recycling technology driven by industry sponsored research have brought new solutions to the issue of blade circularity, making it possible to recycle composite materials with a more readily reusable product and help establish a circular economy for wind turbine blades.[xxiv, xxv]

In the UK, led by the National Composite Centre and delivered in partnership with the Offshore Renewable Energy Catapult and supported by The Crown Estate and RenewableUK, the innovative SusWIND initiative is seeking to discover and demonstrate viable ways to recycle composite wind turbine blades, to explore the use of sustainable materials and processes in developing composites for blades, and to innovate in design to future-proof the turbine blades of tomorrow.[xxvi] SSE Renewables was one of the launch partners for SusWIND in 2020.

A design solution has been developed by Siemens Gamesa, which launched the RecyclableBlade.[xxvii] These blades are designed to be separated at the end of their service life, allowing the materials to be recycled into new applications. Six of these blades have already been produced at a blade manufacturing plant in Aalborg, Denmark and agreements with major customers such as RWE and EDF Renewables have been made to deploy the RecyclableBlades at their offshore wind power plants.

Another use of blade waste has been explored by Fred Olsen Renewables who have teamed up with ReBlade to explore ways of reusing turbine blades at the end of the life cycle by exploring opportunities to repurpose the materials from decommissioned turbine blades into items such as play parks, bus shelters, and bike racks.[xxviii]

The Netherlands Organization for Applied Scientific Research (TNO) and Brightlands Materials Center have also been working on advancing wind blade recycling initiatives by developing a thermochemical process involving pyrolysis to separate the fibres from the composites in the blades, which can then be processed into thermoplastic composites for use in recyclable products.[xxix]

And finally, Vestas have recently announced a breakthrough recycling process that can recycle all wind turbine blades, even ones already sitting in landfills.[xxx, xxxi] The company has developed a novel process that can chemically break down epoxy resin into virgin-grade materials, enabling the martials in epoxy-based turbine blades to become more circular without the need for changing the design or composition of blade material.

These examples show that the wind energy industry is progressing towards establishing a circular economy for turbine blades and tackling the waste problem associated with the materials. As wind energy continues to grow, it will be critical to find sustainable solutions for the entire lifecycle of wind turbines, especially due to the large amounts of parts and components that will be available at the end of the life cycle which could lead to 25,000 tonnes of blades to reach the end of their operational life annually by 2025, rising to 52,000 tonnes by 2030.[xxxii]

[xxiv] https://ore.catapult.org.uk/what-we-do/innovation/circular/

[xxv] https://www.circularonline.co.uk/research-reports/first-steps-to-integrate-circular-economy-into-the-offshore-wind-industry/

[xxvi] https://www.nccuk.com/what-we-do/sustainability/suswind/

[xxvii] https://www.siemensgamesa.com/en-int/newsroom/2021/09/launch-world-first-recyclable-wind-turbine-blade

[xxviii] https://www.scotsman.com/business/partnership-plans-to-turn-used-wind-farm-turbine-blades-into-benches-and-bus-shelters-3725258

[xxix] https://www.compositesworld.com/news/tno-research-offers-circularity-solution-for-discarded-wind-turbine-blades

[xxx] https://electrek.co/2023/02/08/wind-turbine-recycle-blades/

[xxxi] https://www.vestas.com/en/media/company-news/2023/vestas-unveils-circularity-solution-to-end-landfill-for-c3710818

[xxxii] https://windeurope.org/newsroom/press-releases/european-wind-industry-reinforces-sustainability-commitments/#:~:text=WindEurope%20expects%20around%2025%2C000%20tonnes,to%2052%2C000%20tonnes%20by%202030.

4. Skills

Holistically, a circular economy requires a wide range of skills across many different disciplines, including:

- Design skills: The ability to design products, services, and systems that are optimized for circularity, including designing for disassembly, reuse, and recycling
- Innovation skills: The ability to identify new opportunities for circular business models, technologies, and processes, and to develop and implement innovative solutions
- Business skills: The ability to understand and analyse the economic and financial implications of circular business models and to develop effective strategies for circular transition
- Technical skills: The ability to develop and apply new technologies, such as recycling, remanufacturing, and renewable energy, to support circularity
- Collaboration skills: The ability to collaborate effectively with stakeholders across different sectors and disciplines, including business, government, academia, and civil society
- Systems thinking skills: The ability to understand complex systems and to identify and address the systemic barriers to circularity, such as policy, regulation, and market failures
- Data analysis skills: The ability to collect, analyse, and interpret data to support evidence-based decision-making and to track progress towards circular targets
- Communication skills: The ability to communicate complex ideas and concepts to different audiences, including technical and non-technical stakeholders.

4.1. Resource and capabilities gap

Specifically, increasing circularity in wind will require the following services and skills to be available:

- Engineers to diagnose component level integrity, repair and replacement strategies
- Turbine technicians to carry out component removal, refit and commissioning
- Craneage, transport and logistics services
- Warehouse and logistics managers to manage the flow and availability of parts
- Workshop managers to manage the repair and remanufacturing of parts, and
- Workshop technicians, with the requisite component specific level of knowledge and skills to execute repairs and remanufacture.

Of these areas, the skills required in craneage, transportation, logistics and warehouse management are highly transferable from other industries and do not require as high a level of technology specific knowledge and training, therefore are less likely to provide a barrier to growth.

As the global wind industry grows however, it faces a general shortage in engineering and technician skills and finds itself in competition for these skills with other industries.

Diagnostic engineers and technician posts will draw on the same skillsets as required for general turbine technicians. This is likely to be the biggest skills and capability gap, particularly because it requires turbine and component specific knowledge. This likely skills shortage will present a barrier to the growth of circularity in the wind industry and justifies expanding specific skills-based training programmes in this area, such as the wind and marine training network developed by Energy Skills Partnership.[xxxiii]

[xxxiii] https://esp-scotland.ac.uk/wind-marine-training-network/

5. Market analysis

5.1. The model

To estimate the potential market for remanufacturing and refurbishment in the wind industry, we:

- Created capacity timelines of both onshore and offshore wind capacity for the 10 countries under consideration
- Identified the top 10 component and/or sub-systems based on those that have the highest likelihood for either remanufacturing and/or material recovery
- Estimated the refurbishment rates of each component at a global level, broken down by turbine capacity and age
- Combined the above to create a timeline of the total number of refurbishments per year
- Estimated the costs to repair, and avoided waste to scrap, for each of the 10 component refurbishments, and
- Combined the above to create the potential market, estimating gross value add (GVA), full time equivalent jobs (FTE), and avoided waste to scrap for each of the 10 components for each of the 10 countries.

Model context

The model is designed to deliver a top-down forecast of the refurbishment market potential for the 10 included components and for the 10 countries under consideration. It is based on high-level assumptions regarding key inputs including refurbishment rates, refurbishment costs, salaries, project life spans, turbine sizes and component mass. The work does not attempt to model nuances in these assumptions in relation to specific projects, turbine models or commercial practices.

The model is focussed on addressing the potential for refurbishment during the operation of a wind farm, and as such does not consider the substantial additional market opportunity that exists for parts that become available upon wind farm decommissioning.

The model estimates the total potential market, and does not seek to quantify the established market refurbishment.

The full economic potential of refurbishment and remanufacturing in the UK could be significantly higher than the numbers established here if the analysis was extended to include:

- Capabilities for further component parts
- Demand in further countries, and
- Consideration of re-usable parts as they drop out of the operational fleet due to turbine decommissioning.

5.2. Country installation timelines

We considered the following countries in the analysis:

- Belgium
- Denmark
- France
- Germany
- Netherlands
- Poland
- Portugal
- Spain
- Sweden, and

- UK

These are the top 10 European countries by installed onshore and offshore capacity. Installation timelines from 1990 to 2035 were established for each country. In the few instances where countries had installations prior to 1990, these turbines were included in the 1990 figures.

Both offshore and onshore datasets were split into two sections, actual turbine installations and estimates for future installations.

For onshore, the installed capacity up to and including 2021 was established using the Wind Power Monthly (WPM) European onshore wind farm database.[xxxiv] These values were cross-checked against those reported by Statista.[xxxv] Where there was a discrepancy, we cross-checked against both Wikipedia and IEA Wind, adjusting the profiles provided by WPM if required. Future targets for onshore for each country were established via several different references.[xxxvi,xxxvii,xxxviii,xxxix,xl,xli,xlii,xliii,xliv,xlv,xlvi]

For offshore, both the installed and future capacities for each country were taken from BVGA's in-house market intelligence tool. This is based largely on data provided from subscription services and is constantly reviewed and adjusted through BVGA's own industry engagement and market analysis.[xlvii]

For simplicity, we assumed all turbine classes had a design life of 25 years, after which 50% of them would be decommissioned. The remaining 50% would operate for a further 5 years, after which they would also be decommissioned.

For the purposes of this study, "decommissioned" means "removed from the operational fleet".

The model only considers refurbishments within the operational fleet. It does not put any commercial or waste value on the parts that are released through decommissioning.

The estimated capacity and numbers of turbines are shown in Figure 1 and Figure 2. By 2035 we expect to have approximately 584 GW of operational capacity across the 10 countries, provided by around 120,000 turbines.

[xxxiv] https://www.windpowermonthly.com/intelligence?dashboard

[xxxv] https://www.statista.com/

[xxxvi] https://www.elia.be/en/infrastructure-and-projects/investment-plan/federal-development-plan-2020-2030

[xxxvii] https://www.rystadenergy.com/news/finland-denmark-and-sweden-leading-on-the-green-revolution

[xxxviii] https://windeurope.org/newsroom/news/responsible-deployment-of-wind-is-indispensable-for-a-successful-energy-transition-in-france/

[xxxix] https://www.cleanenergywire.org/factsheets/german-onshore-wind-power-output-business-and-perspectives

[xl] https://renews.biz/83579/netherlands-posts-record-onshore-wind-growth/#:~:text=The%20Netherlands%20has%20recorded%202022,total%20cumulative%20installed%20capacity%206223MW

[xli] https://ember-climate.org/insights/commentary/failure-to-remove-barriers-to-polands-onshore-wind-risks-blackouts-and-higher-bills/

[xlii] https://www.mordorintelligence.com/industry-reports/portugal-wind-energy-market

[xliii] https://iea-wind.org/about-iea-wind-tcp/members/spain/#:~:text=According%20to%20the%20Spanish%20National,installed%20842.61%20MW%20during%202021

[xliv] "https://renewablesnow.com/news/finland-denmark-sweden-seen-to-reach-74-gw-of-onshore-wind-solar-by-2030-805133/#:~:text=Sweden%20is%20seen%20to%20install,just%200.8%20GW%20of%20solar

https://www.rystadenergy.com/news/finland-denmark-and-sweden-leading-on-the-green-revolution"

[xlv] "https://renewablesnow.com/news/finland-denmark-sweden-seen-to-reach-74-gw-of-onshore-wind-solar-by-2030-805133/#:~:text=Sweden%20is%20seen%20to%20install,just%200.8%20GW%20of%20solar

https://www.rystadenergy.com/news/finland-denmark-and-sweden-leading-on-the-green-revolution"

[xlvi] https://www.reutersevents.com/renewables/wind/uk-energy-minister-aims-double-onshore-wind-portugal-leaps-large-floating-arrays

[xlvii] https://www.4coffshore.com/

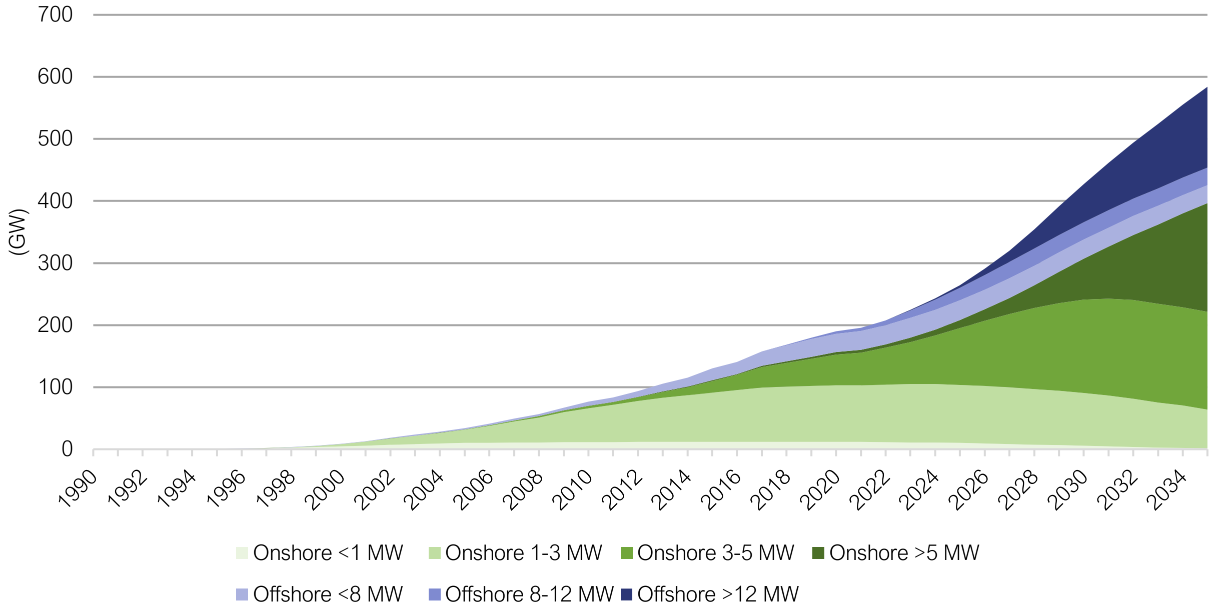
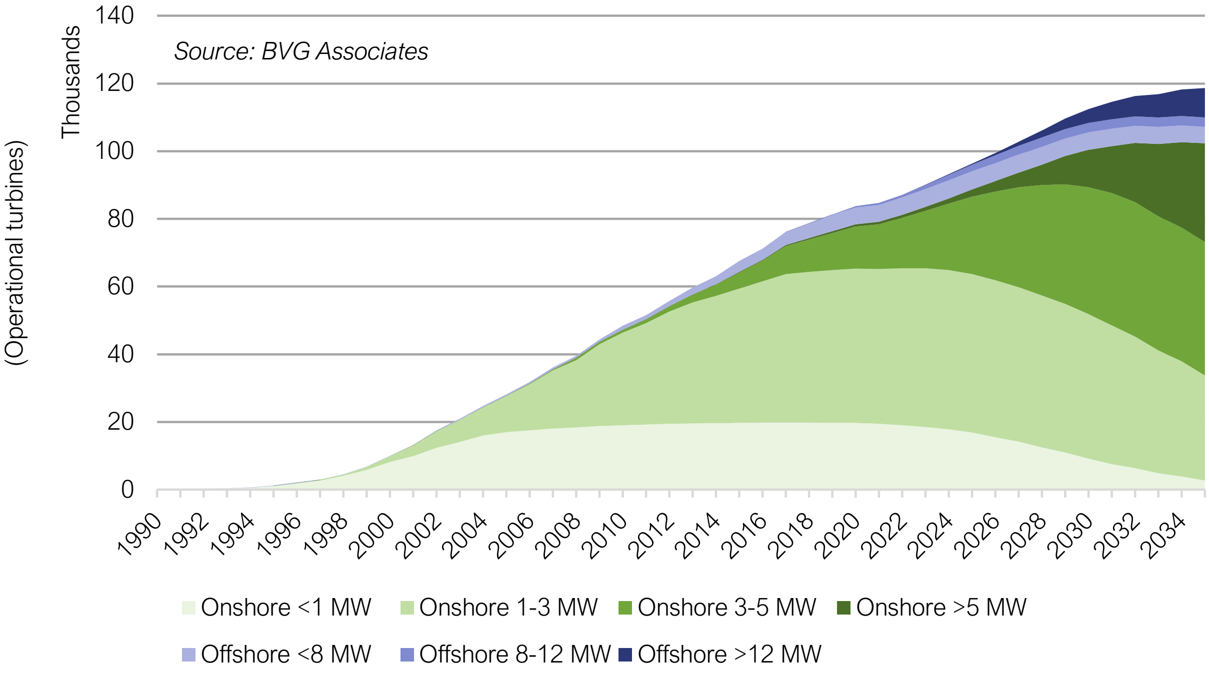


Figure 1 Capacity timeline for the 10 countries



Source: BVG Associates

Figure 2 The estimated number of turbines for the 10 countries

5.3. The top 10 component refurbishments

5.3.1 Components

Through discussion with SSER and RPL, we agreed on the following list of 10 components/sub-assemblies:

- Callipers
- Converters (specifically phase modules)
- Gearbox
- Generator

- Hydraulic station
- Drive shaft assembly
- Slip rings
- Three phase motors
- Transformer, and
- Yaw gears.

These were chosen based on their overall suitability for either remanufacturing or material recovery, considering present industry technology and capability.

Blades were excluded from the analysis as the circularity of blades is a subject area that is arguably more specialised than the components listed above and requires more advanced technical solutions.

5.3.2 Refurbishment rates and age profiling

Using a combination of operational experience, desk-based research and extrapolation, BVGA provided high level estimates of refurbishment rates for each of the 10 components.

For simplicity, we deliberately ignored the potentially large differences in refurbishment rates between geographies, turbine models, etc., seeking to establish generic rates that were appropriate for the level of detail being analysed.

Where justifiable, we identified different rates based on turbine “class” and age. We used the following class and age profiles for all components:

Turbine class

- Onshore <1 MW
- Onshore 1-3 MW
- Onshore 3-5 MW
- Onshore >5 MW
- Offshore <8 MW
- Offshore 8-12 MW
- Offshore >12 MW

Age

- <5 years
- 5 to 10 years
- 11 to 15 years
- 16 to 20 years
- 21 to 25 years
- >25 years

5.3.3 Decommissioning and life extension

For each turbine class, the model can set:

- the design life, and
- the percentage of turbines decommissioned at design life vs life extension.

For simplicity, for all turbine classes we assigned a design life of 25 years and an expectation that 50% of turbines will be life extended for a further 5 years.

The model assumes that 100% of turbines are ultimately decommissioned, either after their design life or after their life extension.

The model only evaluates the market opportunity for operational turbines. The model does not allocate value to parts that are released when a turbine is decommissioned.

5.4. Economic impact

The economic impact was measured using gross value add (GVA) and full time equivalent (FTE) jobs.

The GVA was established using only the costs associated with the act of refurbishment – we ignored costs associated with transport, removal, and installation as these would be incurred regardless of whether a new or refurbished part was being used.

The GVA was split into direct and indirect costs, where direct costs are those incurred directly by the company doing the refurbishment (such as office overheads, staff, vehicles, tools, etc.), and indirect costs are 3rd party costs (such as bought in materials).

The salary related part of GVA is then divided by the average salary to get to a value of FTE.

Induced GVA and FTE (3rd party benefits that are created due to the Direct and Indirect GVA, such as extra revenue for local hotels, shops, cafes, etc.) are then established using a simple ratio.

The overall process is shown in Figure 3.

The model can set these parameters on a component/turbine class basis, though for simplicity we have used the same GVA/FTE ratios throughout. These are summarised in Appendix A.

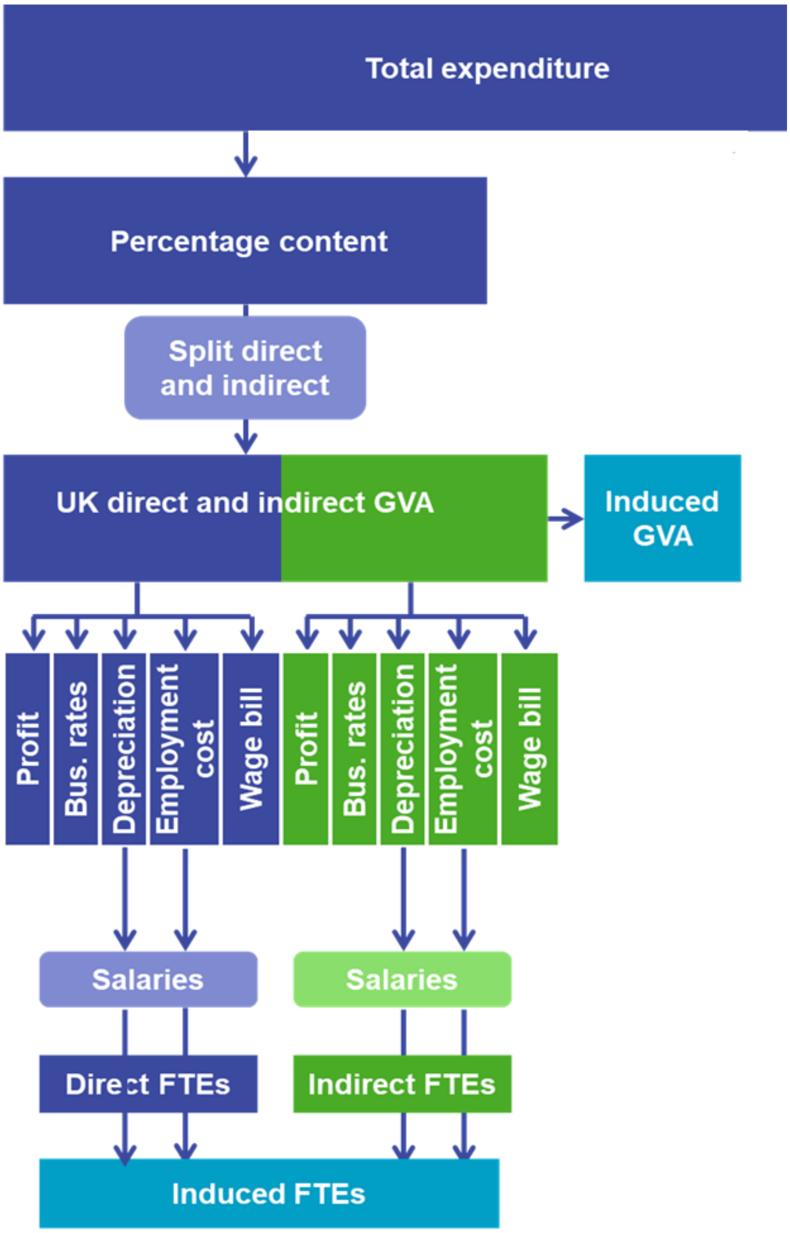


Figure 3 GVA and FTE process

5.5. Environmental impact

Environmental impact was measured in terms of the avoided mass of waste to scrap in kg.

For each component replacement, and for each turbine class, we estimated the mass of waste that would otherwise have been sent to scrap if the replaced part was simply discarded rather than refurbished.

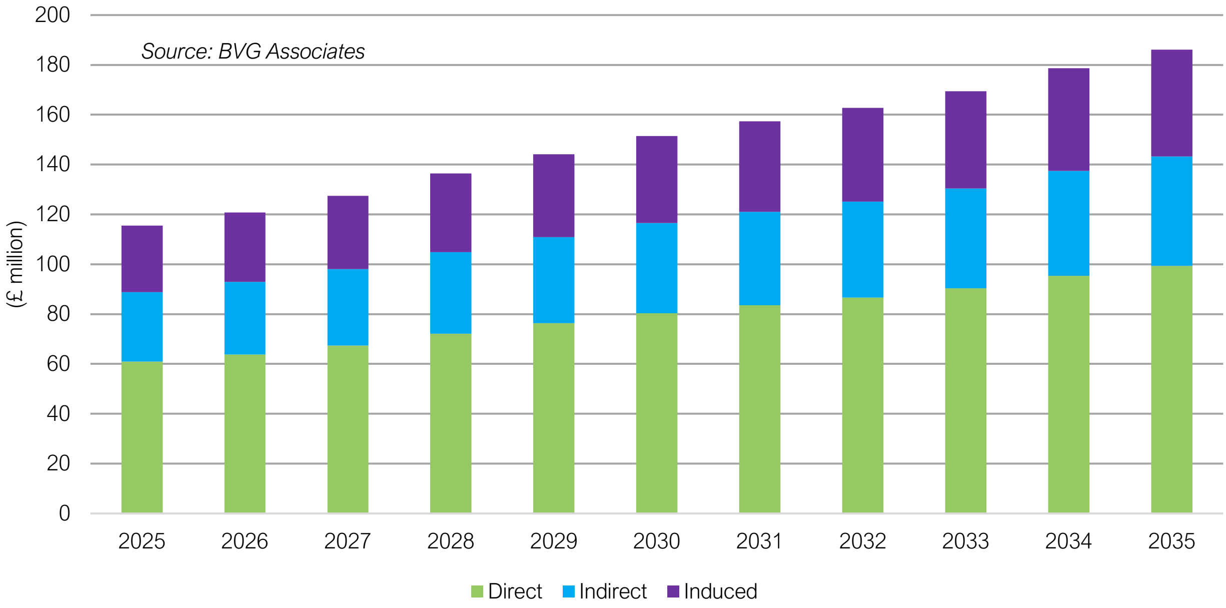
The assumed component masses are shown in Appendix A.

5.6. Results

5.6.1 Potential market

The economic contribution from the potential market for the 10 component parts considered, established as GVA and FTE, is shown in Figure 4 to Figure 7. The key points are:

- Over the period between 2025 and 2035 inclusive, the potential market from UK wind turbines alone is estimated to generate £1.6 billion GVA (Figure 4), made up of:
  - £876 million direct
  - £393 million indirect, and
  - £381 million induced.
- The jobs supported from this demand from the UK market alone in 2025 is estimated at 2,209 FTE, increasing to 3,581 FTE in 2035 (Figure 5).
- The potential market for all 10 countries is estimated at £9.6 billion GVA (Figure 6), made up of:
  - £5,088 million direct
  - £2,293 million indirect, and
  - £2,214 million induced.
- The jobs supported from this demand for all 10 countries in 2025 is estimated at 13,183 FTE, increasing to 20,111 FTE in 2035 (Figure 7).



Source: BVG Associates

Figure 4 Total GVA added by refurbishment (UK only)

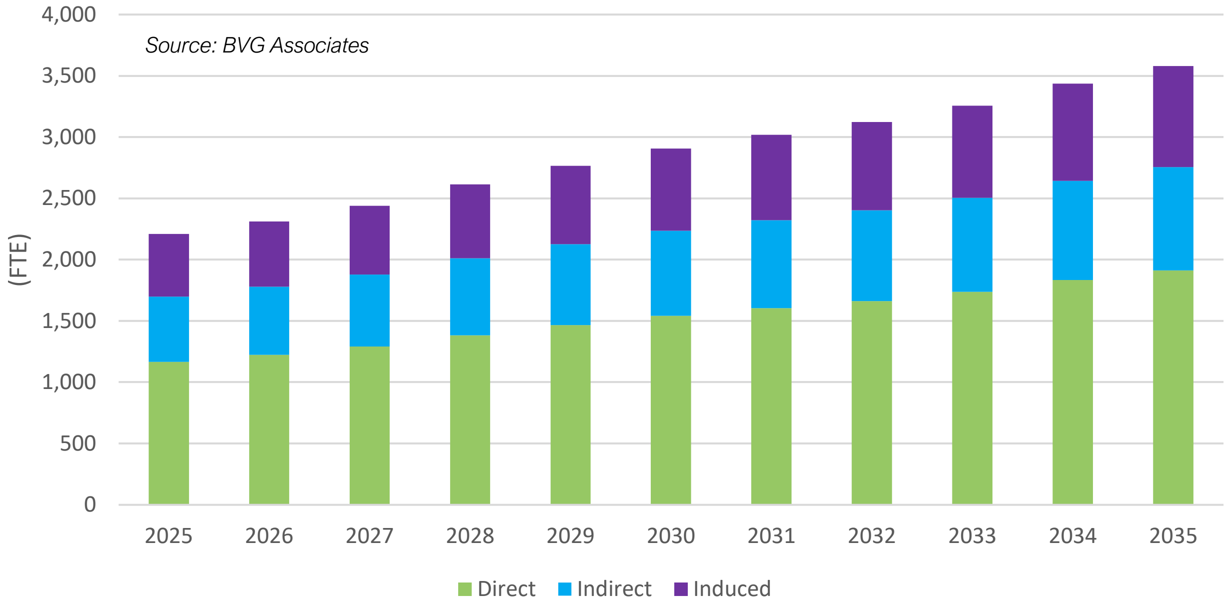


Figure 5 Total FTE per year (UK)

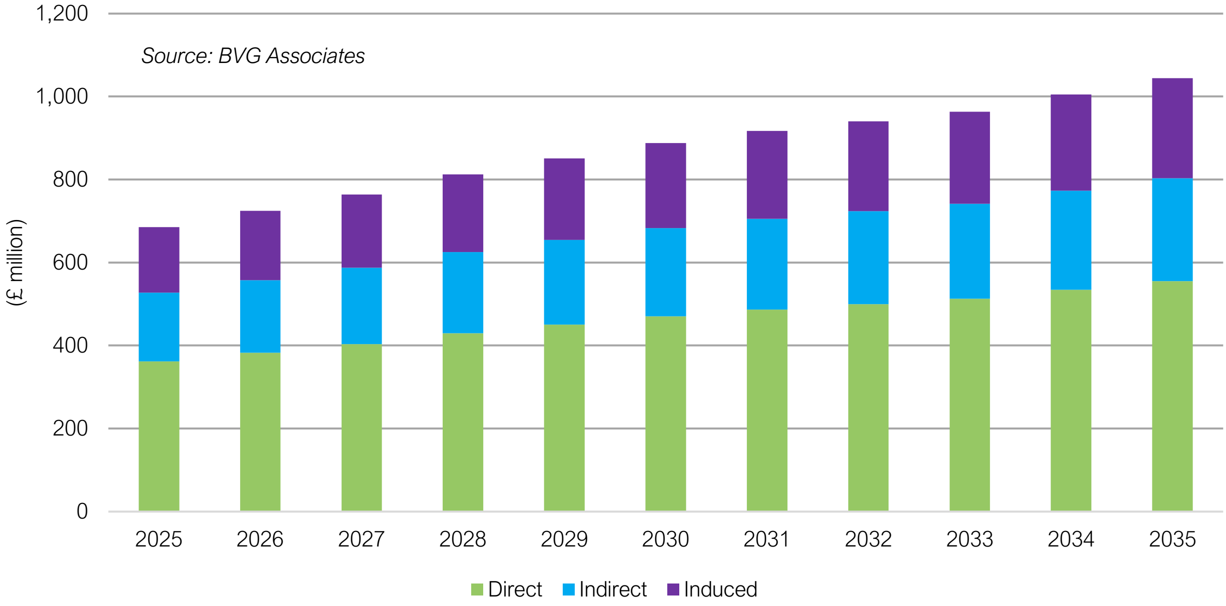
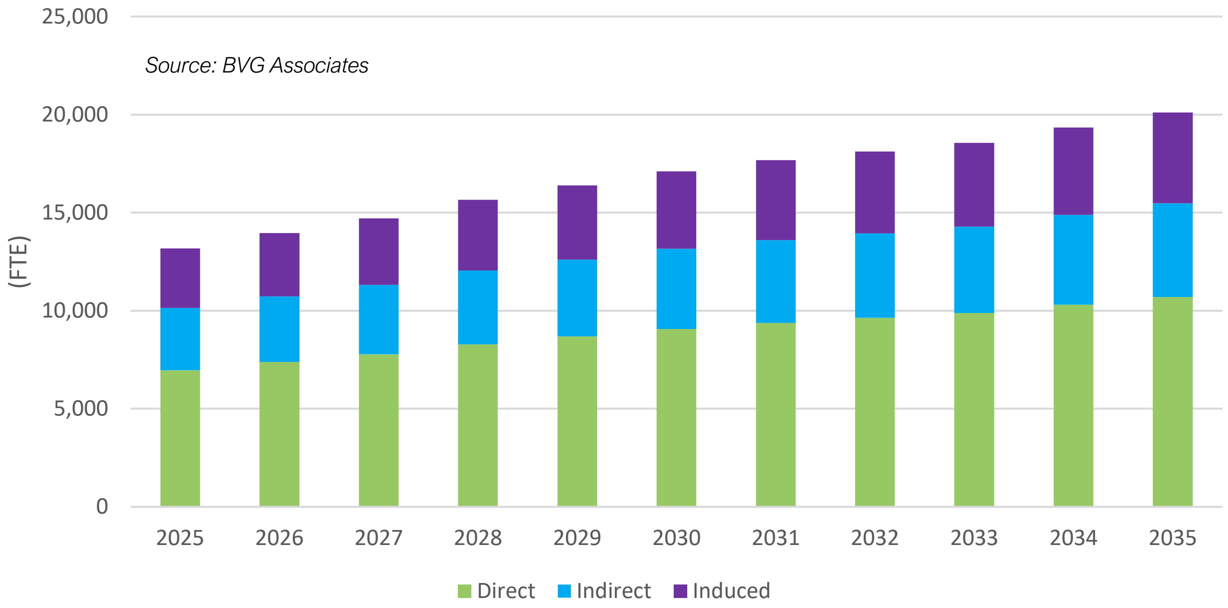


Figure 6 Total GVA added by refurbishment (all countries)

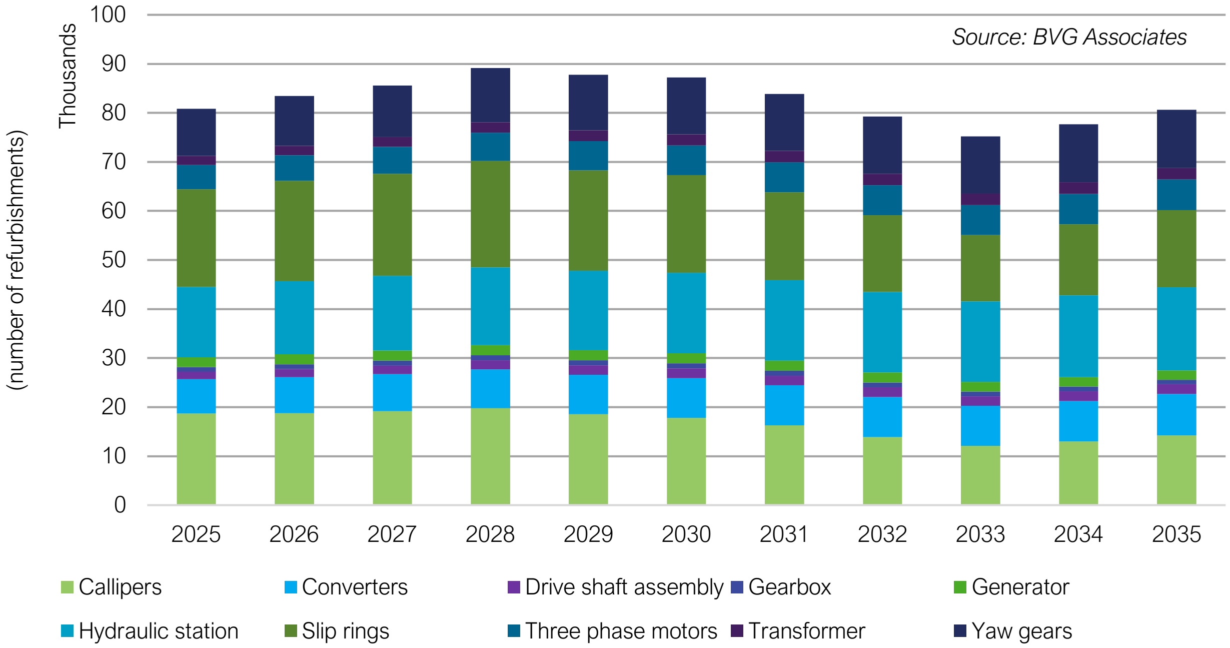


Source: BVG Associates

Figure 7 Total FTE per year (all countries)

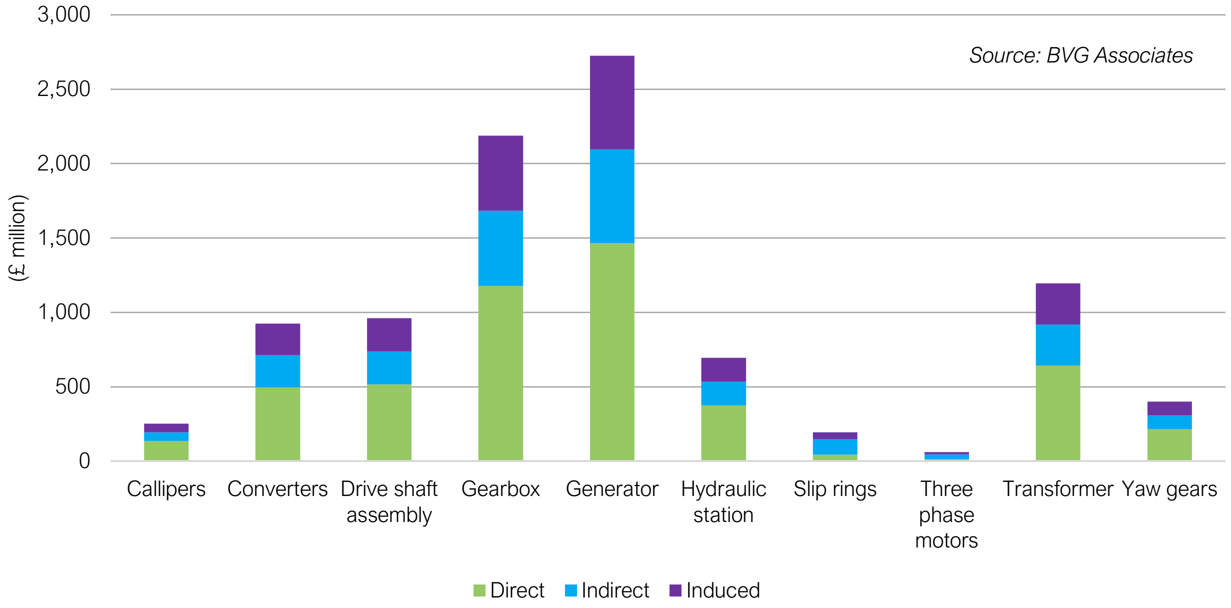
5.6.2 Refurbishments and GVA per component

The total number of refurbishments estimated (for all 10 countries) for each component is shown in Figure 8. While the physically smaller components dominate numerically, converting to GVA shows that the majority of value is provided the gearbox and generator refurbishments, followed by converters, drive shaft assemblies and transformers (Figure 9).



Source: BVG Associates

Figure 8 Total number of refurbishments per year (all countries)



Source: BVG Associates

Figure 9 GVA by component (all countries, 2025 to 2035)

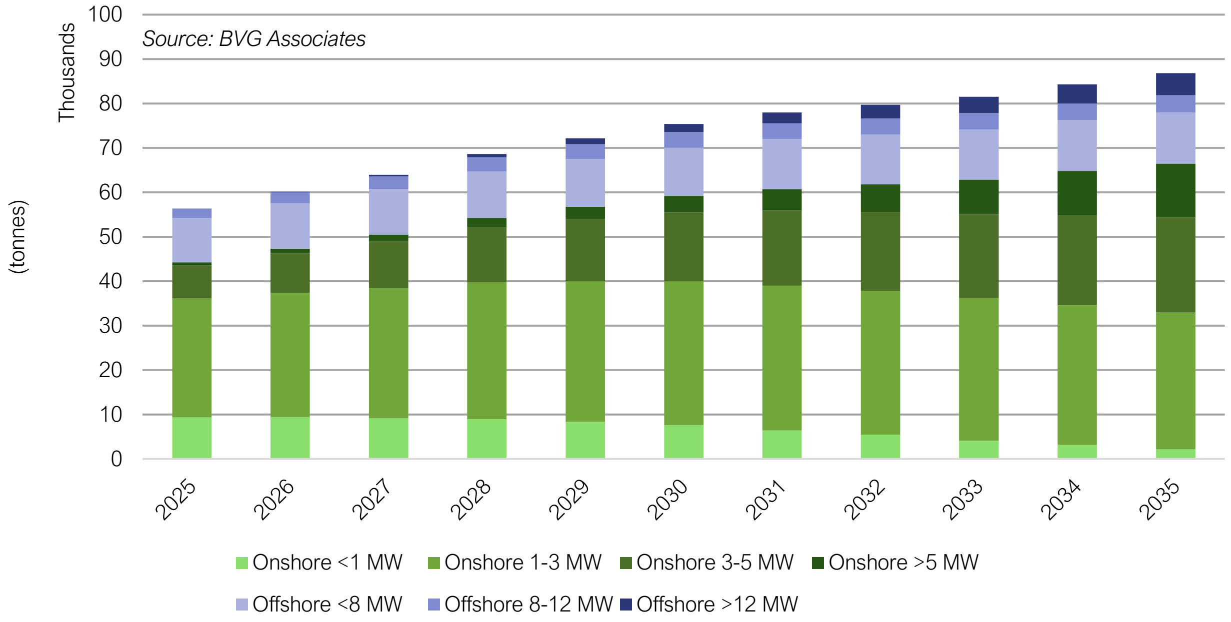
5.6.3 Environmental impact

The environmental impact of the potential market was measured using the metric "avoided waste to scrap".

We estimate that 806,978 tonnes of waste to scrap could be avoided from to 2025 to 2035. As shown in Figure 10, the majority contribution to this comes from the onshore turbines in the 1 to 5 MW class.

Figure 11 shows that the waste comes from the four primary components of drive shaft assembly, gearbox, generator, and transformer.

Figure 12 shows that the countries with the biggest potential for waste savings through refurbishment are Germany, UK, and Spain.



Source: BVG Associates

Figure 10 Waste reduced by turbine class (all countries, 2025 to 2035)

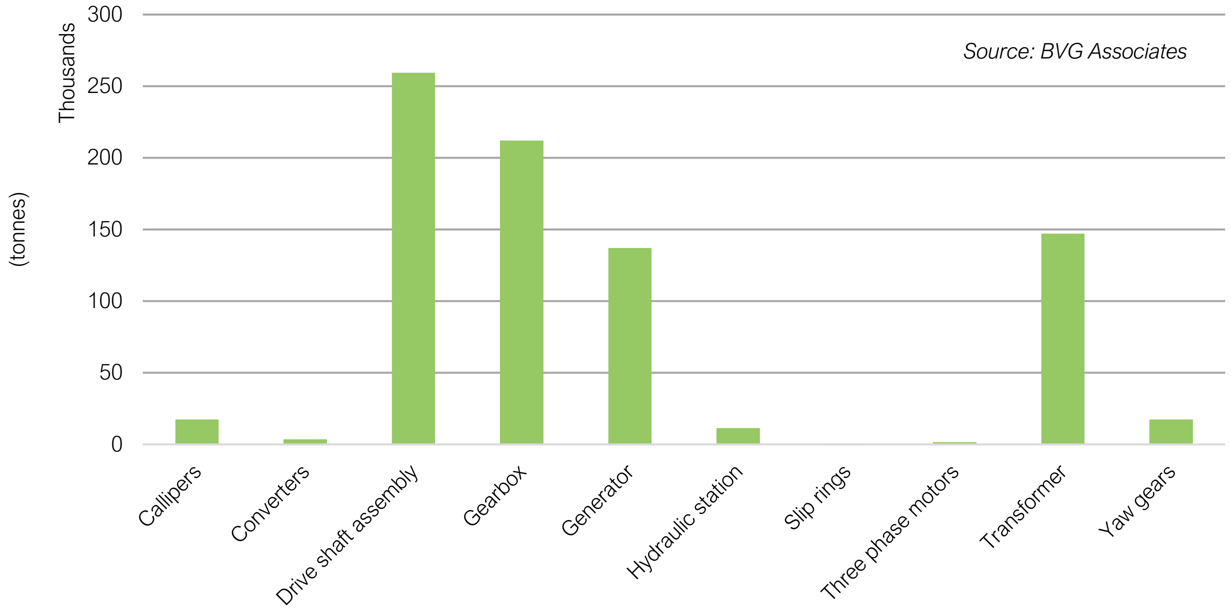


Figure 11 Waste reduced by component (all countries, 2025 to 2035)

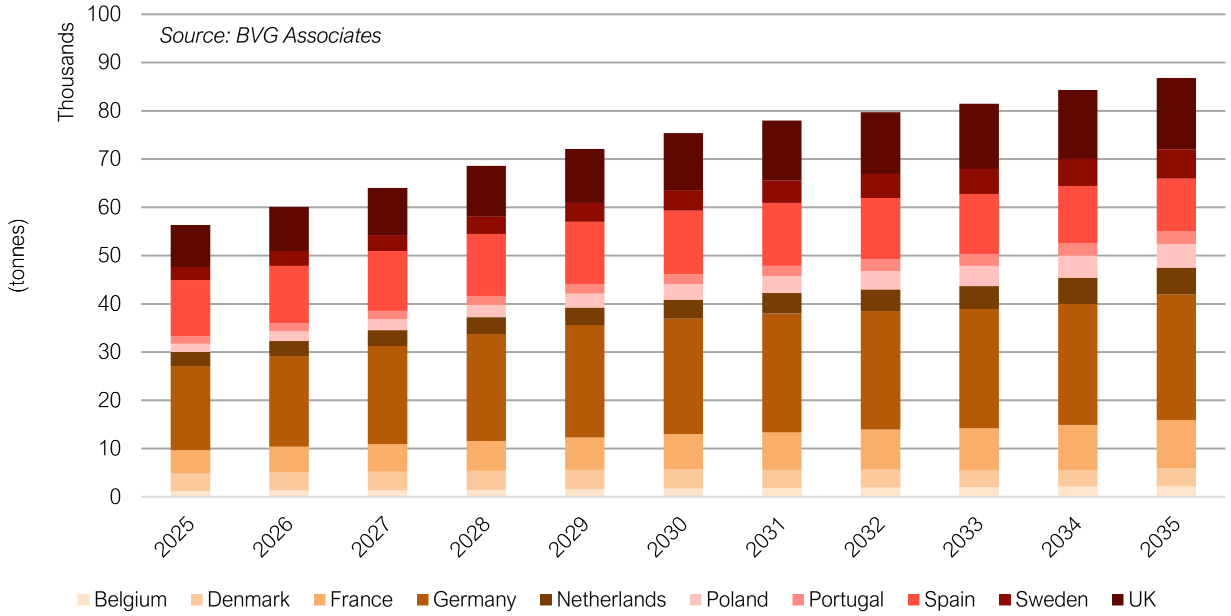


Figure 12 Waste reduced by country

6. Summary

The numbers

The work reported here shows that the potential market driven by the ability to refurbish 10 components from operational wind farms in the UK alone provides an estimated potential UK economic impact of:

- £1.6 billion in GVA for the period between 2025 and 2035
- 2,209 FTE in 2025, increasing to 3,581 FTE in 2035 (the total of direct, indirect, and induced FTEs)
- 129,039 tonnes of avoided waste to scrap for the same period.

Aggregating for all 10 countries, the numbers increase to:

- £9.6 billion in GVA for the same period
- 13,183 FTE in 2025, increasing to 20,111 FTE in 2035 (the total of direct, indirect, and induced FTEs)
- 806,978 tonnes of avoided waste to scrap

For context, it is helpful to compare the totals of £1.6 billion (UK market) and £9.6 billion (all 10 markets) to the estimated £24.9 billion total investment expected from the Scotwind projects.[xlviii]

This report has focussed on the refurbishment opportunity for the operational fleet. It has not estimated the value of parts becoming available as a result of decommissioning. With an estimated 1,500 turbines being decommissioned in the UK over the period 2025 to 2035, this is expected to increase the amount of gearboxes by a factor of 2, drive shaft assemblies by 1.7, and generators by 1.5, therefore significantly increasing the potential economic impact.

The opportunity

It is clear from the work described in this report that the refurbishment market offers a significant opportunity for the UK to establish a market leading supply chain offering which has the benefit of:

- A strong local market with a well-defined future
- Limited competition (if early adopter status is achieved)
- An excellent export market, both at EU level and globally
- Being aligned with significant government policies at Scottish, UK and EU level, and
- Currently being ahead of the political and social pressures driving the underlying need, providing the chance to proactively shape and lead the available opportunity, rather than be led by them.

The risks

This report highlights the general alignment of government policy regarding waste and the circular economy at EU, UK and Scotland Government levels. It also acknowledges, however, that there is little in the way of legal or regulatory obligations on the industry compelling the adoption of circular practices. We warn that the lack of such obligations poses a significant risk of complacency which, if not actively countered, will severely limit the amount of commercial gain that the UK wind industry could benefit from by being an early adopter in the circularity field.

Experience from the aviation and oil and gas industries shows the level of commercial and environmental benefits that can be achieved with a proactive and collaborative approach (aviation) and how easy it is to achieve relatively little (oil and gas) if the process is not carefully and relentlessly managed.

[xlviii] https://www.scottishrenewables.com/news/1089-putting-a-value-on-scotland-s-offshore-wind-revolution

This report highlights the potential skills shortage in the local supply chain which will be a barrier to the industry reaching it's potential if not addressed.

The importance of standards

The role of international standards in this vision should not be ignored. There is a growing level of support for circularity in the standards agencies, including the IEC and BSI, with various IEC standards, technical reports, and technical committees which address specific areas of circularity having particular relevance to the wind industry, including:

- IEC 62309 examines the dependability of products containing used parts.[xlix]
- IEC 62430 sets requirements and provides guidance on implementing environmentally conscious design (ECD).[l]
- IEC TR 62635 provides information on product end-of-life, including the recyclability rate calculation.[li]
- IEC TR 62824 provides guidance about material efficiency considerations in the eco-design of products.[lii]
- TC 2 is developing standards for rotating machinery.[liii]
- TC 111 is working on a standard for assessing the proportion of reused components in products.[liv]

We would encourage the wind industry to take a proactive approach in identifying parts of the refurbishment process which would benefit from standardisation and to actively support and promote the development of these through the appropriate channels. This is one of many key "early adopter" moves that would allow the UK's wind industry to stay at the forefront of this opportunity, driving the opportunity forwards on the international stage.

[xlix] https://webstore.iec.ch/publication/6800

[l] https://webstore.iec.ch/publication/30879

[li] https://webstore.iec.ch/publication/7292

[lii] https://webstore.iec.ch/publication/24658

[liii] https://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID:1221

[liv] https://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID:1314

Appendix A Refurbishment rates, costs and waste

Callipers

	Replacemet rates (Turbine age (years))						Failures that can be refurb'd (%)	Expenditure per refurb (£k)	Avoided waste to scrap per refurb (kg)	GVA per refurb (£k)			FTE per refurb		
	<5	5-10	11-15	16-20	21-25	>25				Direct	Indirect	Induced	Direct	Indirect	Induced
Onshore <1 MW	0%	2%	100%	2%	2%	2%	80	0.3	24	0.2	0.1	0.1	0.0	0.0	0.0
Onshore 1-3 MW	0%	2%	100%	2%	2%	2%	80	0.9	80	0.6	0.3	0.3	0.0	0.0	0.0
Onshore 3-5 MW	0%	2%	100%	2%	2%	2%	80	1.8	160	1.3	0.5	0.5	0.0	0.0	0.0
Onshore >5 MW	0%	2%	100%	2%	2%	2%	80	1.8	160	1.3	0.5	0.5	0.0	0.0	0.0
Offshore <8 MW	2%	10%	10%	2%	2%	2%	80	1.8	160	1.3	0.5	0.5	0.0	0.0	0.0
Offshore 8-12 MW	2%	10%	10%	2%	2%	2%	80	3.0	267	2.1	0.9	0.9	0.0	0.0	0.0
Offshore >12 MW	2%	10%	10%	2%	2%	2%	80	4.5	400	3.2	1.4	1.4	0.1	0.0	0.0

Replacement rates:

- Values are based on operational experience, and include a planned full replacement mid-life.
- Offshore experience shows only limited planned replacement.
- Based on operational experience, 80% of replaced parts are considered repairable.

Economics:

- Direct/indirect ratio set to 70/30, based on experience.
- Cost and waste data points based on experience for Onshore 3-5 MW, >5 MW, and, Offshore <8 MW. Missing points were extrapolated based on turbine size.

Converters (phase modules)

	Replacemet rates (Turbine age (years))						Failures that can be refurb'd (%)	Expenditure per refurb (£k)	Avoided waste to scrap per refurb (kg)	GVA per refurb (£k)			FTE per refurb		
	<5	5-10	11-15	16-20	21-25	>25				Direct	Indirect	Induced	Direct	Indirect	Induced
Onshore <1 MW	0%	5%	8%	8%	8%	10%	100	1.8	9	1.3	0.5	0.5	0.0	0.0	0.0
Onshore 1-3 MW	0%	5%	8%	8%	8%	10%	100	6.0	30	4.2	1.8	1.8	0.1	0.0	0.0
Onshore 3-5 MW	0%	5%	8%	8%	8%	10%	100	12.0	60	8.4	3.6	3.6	0.2	0.1	0.1
Onshore >5 MW	0%	5%	8%	8%	8%	10%	100	12.0	60	8.4	3.6	3.6	0.2	0.1	0.1
Offshore <8 MW	30%	15%	24%	24%	24%	30%	100	12.0	60	8.4	3.6	3.6	0.2	0.1	0.1
Offshore 8-12 MW	15%	10%	16%	16%	16%	20%	100	20.0	100	14.0	6.0	6.0	0.3	0.1	0.1
Offshore >12 MW	0%	5%	8%	8%	8%	10%	100	30.0	150	21.0	9.0	9.0	0.4	0.2	0.2

Replacement rates:

- Onshore values are based on operational experience.
- Offshore values are based on previous work by BVGA, which showed replacement rates 3-4 times that of onshore for early (<8 MW) offshore turbines. A high instance of infant mortality (parts failing within 1 to 2 years of installation) was observed, which we have replicated in the profiles.
- We assume that later offshore models (>12 MW) will have addressed systemic issues and will converge with mature onshore turbines.
- Based on operational experience, 100% of replaced parts are considered repairable.

Economics:

- Direct/indirect ratio assumed to be 70/30.
- Cost and waste data points based on experience for Onshore 1-3 MW, 3-5 MW, >5 MW and Offshore <8 MW. Missing points were extrapolated based on turbine size.

Drive shaft assembly

	Replacemet rates (Turbine age (years))						Failures that can be refurb'd (%)	Expenditure per refurb (£k)	Avoided waste to scrap per refurb (kg)	GVA per refurb (£k)			FTE per refurb		
	<5	5-10	11-15	16-20	21-25	>25				Direct	Indirect	Induced	Direct	Indirect	Induced
Onshore <1 MW	0%	0%	1%	2%	3%	4%	100	20.0	8,000	14.0	6.0	6.0	0.3	0.1	0.1
Onshore 1-3 MW	0%	0%	1%	2%	3%	4%	100	30.0	12,000	21.0	9.0	9.0	0.5	0.2	0.2
Onshore 3-5 MW	0%	0%	1%	2%	3%	4%	100	60.0	16,667	42.0	18.0	18.0	1.0	0.4	0.4
Onshore >5 MW	0%	0%	1%	2%	3%	4%	100	90.0	25,000	63.0	27.0	27.0	1.4	0.6	0.6
Offshore <8 MW	2%	2%	2%	3%	4%	5%	100	90.0	25,000	63.0	27.0	27.0	1.4	0.6	0.6
Offshore 8-12 MW	1%	1%	1%	2%	3%	4%	100	116.2	32,275	81.3	34.9	34.9	1.9	0.8	0.8
Offshore >12 MW	0%	0%	1%	2%	3%	4%	100	142.3	39,528	99.6	42.7	42.7	2.3	1.0	1.0

Replacement rates:

- Data points for Onshore <1 MW, 1-3 MW, 3-5 MW and Offshore <8 MW were provided based on operational experience.
- However, the replacement rates were higher than external sources have observed (typically 1-2%, with little distinction between onshore and offshore) so we reduced the operational observations to be more in line with the wider body of evidence.[lv,lvi,lvii,lviii]
- Based on operational experience, 100% of replaced parts are considered repairable.

Economics:

- Cost and waste data points were provided for Onshore <1 MW, 1-3 MW, 3-5 MW and Offshore <8 MW. Missing points were extrapolated based on turbine size.
- Direct/indirect ratio assumed to be 70/30.

Gearbox

	Replacemet rates (Turbine age (years))						Failures that can be refurb'd (%)	Expenditure per refurb (£k)	Avoided waste to scrap per refurb (kg)	GVA per refurb (£k)			FTE per refurb		
	<5	5-10	11-15	16-20	21-25	>25				Direct	Indirect	Induced	Direct	Indirect	Induced
Onshore <1 MW	2%	2%	2%	2%	2%	2%	95	60.0	3,600	42.0	18.0	18.0	0.8	0.3	0.3
Onshore 1-3 MW	1%	1%	1%	1%	1%	1%	95	109.0	12,825	76.3	32.7	32.7	1.4	0.6	0.6
Onshore 3-5 MW	1%	1%	1%	1%	1%	1%	95	220.0	31,500	154.0	66.0	66.0	2.9	1.2	1.2
Onshore >5 MW	1%	1%	1%	1%	1%	1%	80	350.0	47,250	245.0	105.0	105.0	4.6	2.0	2.0
Offshore <8 MW	2%	2%	2%	2%	2%	2%	80	350.0	47,250	245.0	105.0	105.0	4.6	2.0	2.0
Offshore 8-12 MW	1%	1%	1%	1%	1%	1%	80	451.8	60,999	316.3	135.6	135.6	5.9	2.5	2.5
Offshore >12 MW	1%	1%	1%	1%	1%	1%	80	553.4	74,709	387.4	166.0	166.0	7.2	3.1	3.1

Replacement rates:

- Onshore values are based on operational experience. These are significantly lower than various publicly available studies, but we rationalise that this is down to:[lv,lvi,lvii,lviii]
    - improved O&M practices across all turbine classes
    - improved design for the 3-5 and > 5 MW classes
    - improved monitoring for the 3-5 and >5 MW classes, with increased use of oil filtration and CMS designed in, and
    - improved monitoring and analytics across the board, with retrofitted oil filtration and CMS increasingly applied to the earlier <1 MW and 1-3 MW classes.
- Operational experience shows that the early onshore models (<1 MW) have a greater replacement rate (approximately x2) of later models.

[lv] https://cordis.europa.eu/project/id/212966/reporting

[lvi] https://strathprints.strath.ac.uk/54141/1/Carroll_etal_WE_2015_Failure_rate_repair_time_and_unscheduled_O_and_M_cost_analysis_of_offshore.pdf

[lvii] https://www.mdpi.com/2077-1312/10/12/1965

[lviii] https://onlinelibrary.wiley.com/doi/full/10.1002/we.2404

- This is higher rate has also been observed for early offshore models (<8 MW), but we assume that later offshore models will have addressed systemic issues and will converge with mature onshore turbines.
- Based on operational experience, 95% of replaced parts are considered repairable. We have reduced this to 80% for larger models to accommodate the greater instance of direct drive models in these classes.

Economics:

- Direct/indirect ratio assumed to be 70/30.
- Data points based on experience used for Onshore 1-3 MW, 3-5 MW, >5 MW and Offshore <8 MW. Missing points were extrapolated based on turbine size.

Generator

	Replacemet rates (Turbine age (years))						Failures that can be refurb'd (%)	Expenditure per refurb (£k)	Avoided waste to scrap per refurb (kg)	GVA per refurb (£k)			FTE per refurb		
	<5	5-10	11-15	16-20	21-25	>25				Direct	Indirect	Induced	Direct	Indirect	Induced
Onshore <1 MW	3%	3%	3%	3%	3%	3%	95	52.0	3,384	36.4	15.6	15.6	0.7	0.3	0.3
Onshore 1-3 MW	2%	2%	2%	2%	2%	2%	95	75.0	6,120	52.5	22.5	22.5	1.0	0.4	0.4
Onshore 3-5 MW	1%	1%	1%	1%	1%	1%	95	106.7	7,245	74.7	32.0	32.0	1.4	0.6	0.6
Onshore >5 MW	1%	1%	1%	1%	1%	1%	95	160.0	9,000	112.0	48.0	48.0	2.1	0.9	0.9
Offshore <8 MW	4%	4%	4%	4%	4%	4%	95	160.0	9,000	112.0	48.0	48.0	2.1	0.9	0.9
Offshore 8-12 MW	2%	2%	2%	2%	2%	2%	95	266.7	11,619	186.7	80.0	80.0	3.5	1.5	1.5
Offshore >12 MW	1%	1%	1%	1%	1%	1%	95	400.0	14,230	280.0	120.0	120.0	5.2	2.2	2.2

Replacement rates:

- Onshore values are based on operational experience and set at approximately twice that of gearbox replacement rates. These are significantly lower than various publicly available studies, but we rationalise that this is down to improved O&M practices across all turbine classes.[lv,lvi,lvii,lviii]
- Based on operational experience, 95% of replaced parts are considered repairable.

Economics:

- Direct/indirect ratio assumed to be 70/30.
- Cost and waste data points based on experience for Onshore 1-3 MW, 3-5 MW, >5 MW and Offshore <8 MW. Missing points were extrapolated based on turbine size.

Hydraulic station

	Replacemet rates (Turbine age (years))						Failures that can be refurb'd (%)	Expenditure per refurb (£k)	Avoided waste to scrap per refurb (kg)	GVA per refurb (£k)			FTE per refurb		
	<5	5-10	11-15	16-20	21-25	>25				Direct	Indirect	Induced	Direct	Indirect	Induced
Onshore <1 MW	0%	10%	20%	20%	20%	20%	100	0.8	16	0.5	0.2	0.2	0.0	0.0	0.0
Onshore 1-3 MW	0%	10%	20%	20%	20%	20%	100	2.5	53	1.8	0.8	0.8	0.0	0.0	0.0
Onshore 3-5 MW	0%	10%	20%	20%	20%	20%	100	5.0	105	3.5	1.5	1.5	0.1	0.0	0.0
Onshore >5 MW	0%	10%	20%	20%	20%	20%	100	5.0	105	3.5	1.5	1.5	0.1	0.0	0.0
Offshore <8 MW	0%	10%	20%	20%	20%	20%	100	5.0	105	3.5	1.5	1.5	0.1	0.0	0.0
Offshore 8-12 MW	0%	10%	20%	20%	20%	20%	100	8.3	175	5.8	2.5	2.5	0.1	0.0	0.0
Offshore >12 MW	0%	10%	20%	20%	20%	20%	100	12.5	263	8.8	3.8	3.8	0.2	0.1	0.1

Replacement rates:

- Values are based on operational experience and are aligned with observations from previous studies.[lv,lvi,lvii,lviii]
- Based on operational experience, 100% of replaced parts are considered repairable.

Economics:

- Direct/indirect ratio assumed to be 70/30.
- Cost and waste data points based on experience for Onshore 3-5 MW, >5 MW and Offshore <8 MW. Missing points were extrapolated based on turbine size.

Slip rings

	Replacemet rates (Turbine age (years))						Failures that can be refurb'd (%)	Expenditure per refurb (£k)	Avoided waste to scrap per refurb (kg)	GVA per refurb (£k)			FTE per refurb		
	<5	5-10	11-15	16-20	21-25	>25				Direct	Indirect	Induced	Direct	Indirect	Induced
Onshore <1 MW	0%	2%	100%	2%	2%	2%	60	1.0	5	0.3	0.7	0.3	0.0	0.0	0.0
Onshore 1-3 MW	0%	2%	100%	2%	2%	2%	60	1.2	5	0.4	0.8	0.4	0.0	0.0	0.0
Onshore 3-5 MW	0%	2%	100%	2%	2%	2%	60	1.2	5	0.4	0.8	0.4	0.0	0.0	0.0
Onshore >5 MW	0%	2%	100%	2%	2%	2%	60	1.5	5	0.5	1.1	0.5	0.0	0.0	0.0
Offshore <8 MW	0%	2%	100%	2%	2%	2%	60	1.5	5	0.5	1.1	0.5	0.0	0.0	0.0
Offshore 8-12 MW	0%	2%	100%	2%	2%	2%	60	1.7	5	0.5	1.2	0.5	0.0	0.0	0.0
Offshore >12 MW	0%	2%	100%	2%	2%	2%	60	1.9	5	0.6	1.3	0.6	0.0	0.0	0.0

Replacement rates:

- Data points for Onshore 1-3 MW, 3-5 MW, >5 MW and Offshore <8 MW all based on operational experience. Missing data were extrapolated from these points.
- Based on operational experience, 60% of replaced parts are considered repairable.

Economics:

- Data points for Onshore 1-3 MW, 3-5 MW, >5 MW and, Offshore <8 MW all based on operational experience. Missing data were extrapolated from these points.
- Direct/indirect ratio assumed to be 70/30.

Three phase motors

	Replacemet rates (Turbine age (years))						Failures that can be refurb'd (%)	Expenditure per refurb (£k)	Avoided waste to scrap per refurb (kg)	GVA per refurb (£k)			FTE per refurb		
	<5	5-10	11-15	16-20	21-25	>25				Direct	Indirect	Induced	Direct	Indirect	Induced
Onshore <1 MW	0%	2%	5%	8%	8%	10%	100	0.3	10	0.1	0.2	0.1	0.0	0.0	0.0
Onshore 1-3 MW	0%	2%	5%	8%	8%	10%	100	0.8	20	0.2	0.6	0.2	0.0	0.0	0.0
Onshore 3-5 MW	0%	2%	5%	8%	8%	10%	100	0.8	30	0.2	0.6	0.2	0.0	0.0	0.0
Onshore >5 MW	0%	2%	5%	8%	8%	10%	100	1.2	30	0.4	0.8	0.4	0.0	0.0	0.0
Offshore <8 MW	0%	2%	5%	8%	8%	10%	100	1.2	50	0.4	0.8	0.4	0.0	0.0	0.0
Offshore 8-12 MW	0%	2%	5%	8%	8%	10%	100	1.4	60	0.4	1.0	0.4	0.0	0.0	0.0
Offshore >12 MW	0%	2%	5%	8%	8%	10%	100	1.6	70	0.5	1.1	0.5	0.0	0.0	0.0

Replacement rates:

- Data points for Onshore (all classes) and Offshore <8 MW all based on operational experience. Missing data were extrapolated from these points.
- Based on operational experience, 100% of replaced parts are considered repairable.

Economics:

- Data points for Onshore (all classes) and Offshore <8 MW all based on operational experience. Missing data were extrapolated from these points.
- Direct/indirect ratio assumed to be 70/30.

Transformer

	Replacemet rates (Turbine age (years))						Failures that can be refurb'd (%)	Expenditure per refurb (£k)	Avoided waste to scrap per refurb (kg)	GVA per refurb (£k)			FTE per refurb		
	<5	5-10	11-15	16-20	21-25	>25				Direct	Indirect	Induced	Direct	Indirect	Induced
Onshore <1 MW	1%	1%	2%	2%	3%	3%	100	8.4	2,700	5.9	2.5	2.5	0.1	0.0	0.0
Onshore 1-3 MW	1%	1%	2%	2%	3%	3%	100	28.0	5,100	19.6	8.4	8.4	0.4	0.2	0.2
Onshore 3-5 MW	1%	1%	2%	2%	3%	3%	100	56.0	7,650	39.2	16.8	16.8	0.7	0.3	0.3
Onshore >5 MW	1%	1%	2%	2%	3%	3%	100	84.0	11,475	58.8	25.2	25.2	1.1	0.5	0.5
Offshore <8 MW	1%	1%	2%	2%	3%	3%	100	84.0	11,475	58.8	25.2	25.2	1.1	0.5	0.5
Offshore 8-12 MW	1%	1%	2%	2%	3%	3%	100	108.4	14,814	75.9	32.5	32.5	1.4	0.6	0.6
Offshore >12 MW	1%	1%	2%	2%	3%	3%	100	102.9	14,054	72.0	30.9	30.9	1.3	0.6	0.6

Replacement rates:

- Data points for Offshore <8 MW were based on operational experience. These were aligned with data points available from external studies, so we used throughout. [lv,lvi,lvii,lviii]

- It is estimated that 100% of replaced parts are considered repairable.

Economics:

- A data point for GVA was provided for Offshore <8 MW. We extrapolated from this to estimate the missing data.
- Direct/indirect ratio assumed to be 70/30.

Yaw gears.

	Replacemet rates (Turbine age (years))						Failures that can be refurb'd (%)	Expenditure per refurb (£k)	Avoided waste to scrap per refurb (kg)	GVA per refurb (£k)			FTE per refurb		
	<5	5-10	11-15	16-20	21-25	>25				Direct	Indirect	Induced	Direct	Indirect	Induced
Onshore <1 MW	2%	5%	10%	15%	15%	15%	100	2.5	100	1.8	0.8	0.8	0.0	0.0	0.0
Onshore 1-3 MW	2%	5%	10%	15%	15%	15%	100	2.5	140	1.8	0.8	0.8	0.0	0.0	0.0
Onshore 3-5 MW	2%	5%	10%	15%	15%	15%	50	4.0	200	2.8	1.2	1.2	0.1	0.0	0.0
Onshore >5 MW	2%	5%	10%	15%	15%	15%	50	4.0	350	2.8	1.2	1.2	0.1	0.0	0.0
Offshore <8 MW	2%	5%	10%	15%	15%	15%	75	5.0	350	3.5	1.5	1.5	0.1	0.0	0.0
Offshore 8-12 MW	2%	5%	10%	15%	15%	15%	75	7.0	583	4.9	2.1	2.1	0.1	0.0	0.0
Offshore >12 MW	2%	5%	10%	15%	15%	15%	75	7.0	875	4.9	2.1	2.1	0.1	0.0	0.0

Replacement rates:

- Data points for all onshore models were based on operational experience. We have assumed the offshore values to be the same.
- It is observed that 100% of replaced parts are repairable for smaller onshore models, but this reduces to 50% for the larger models. We assumed that offshore will be 75%.

Economics:

- Data points for GVA and waste were provided for Onshore (all) and Offshore <8 MW. We extrapolated from these to estimate the missing data.
- Direct/indirect ratio assumed to be 70/30.

BVGAssociates

About BVG Associates

BVG Associates is an independent renewable energy consultancy focussing on wind, wave and tidal, and energy systems. Our clients choose us when they want to do new things, think in new ways and solve tough problems. Our expertise covers the business, economics and technology of renewable energy generation systems. We're dedicated to helping our clients establish renewable energy generation as a major, responsible and cost-effective part of a sustainable global energy mix. Our knowledge, hands-on experience and industry understanding enables us to deliver you excellence in guiding your business and technologies to meet market needs.

- BVG Associates was formed in 2006 at the start of the offshore wind industry.
- We have a global client base, including customers of all sizes in Europe, North America, South America, Asia and Australia.
- Our highly experienced team has an average of over 10 years' experience in renewable energy.
- Most of our work is advising private clients investing in manufacturing, technology and renewable energy projects.
- We've also published many landmark reports on the future of the industry, cost of energy and supply chain.