The future of onshore wind decommissioning in Scotland

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Contents

Executive Summary

Zero Waste Scotland commissioned Jacobs to undertake a market research project to quantify the profile of onshore wind decommissioning in Scotland up to 2050. The project provides an objective market assessment to forecast the potential volumes of material associated with decommissioned wind turbines and identifies circular economy opportunities to enable cost effective and sustainable development of the Scottish onshore wind market. Market research was conducted with organisations involved in onshore wind industry in the form of a questionnaire and interviews to inform and validate findings.

There are limited published studies on the scale of the onshore decommissioning market in Scotland and forecasts of material volumes are often cited as a barrier to develop this market. However, significant circular economy opportunities exist through the reuse, refurbishment and repurposing of components and material. The adoption of a circular economy for decommissioned wind turbines also offers the opportunity to reduce carbon emissions, improve material management, create skills and job opportunities, and add value to the Scottish economy.

To quantify the profile of onshore wind decommissioning in Scotland a model was developed using the Renewable UK Database with assumptions applied. As explained in Section 2 of the report, the model estimated that there will be 4,894 turbines in Scotland decommissioned in a low decommissioning forecast scenario and 5,613 in a high decommissioning forecast from 2021 to 2050.

Treatment options for decommissioned onshore wind turbines and their components have been identified, described, and evaluated using a multicriteria assessment (MCA) in Section 3 of the report. The MCA identifies that treatment options with higher resource efficiency, such as life extension, refurbishment and reuse, offer the greatest value to Scotland and the industry through economic growth and retention of resources and development of skills within the Scottish economy. This task also concluded that the supply chain in Scotland for employing circular processes and a lack of existing facilities are a barrier for value retention in Scotland.

A cost assessment for a typical 2MW turbine is presented in Section 4 of the report and was developed for refurbishment, reuse, recycling, and disposal to identify possibilities of generating revenue through each of these treatment options. A series of high level calculations concluded that the treatment options that employ greater resource efficiency offer the best potential return as measured financially and through Gross Value Added (GVA).

A carbon assessment (Section 5 of the report) was undertaken and identified an approximate potential emission savings of 35% from the manufacturing of wind turbines using recycled content compared to virgin materials. An assessment of emissions from transport of decommissioned turbines from each of Scotland's Local Authorities to three representative coastal locations in northern, central and southern Scotland found that a port located on the central east coast would result in the lowest emissions of the three locations. This followed an investigation into the process of storing and separating decommissioned materials in Section 6 of the report where ports were found to provide an opportunity for locating a potential decommissioning hub as they have the potential space for equipment and infrastructure and may already have experience with the wind industry.

Section 7 of the report presents a number of recommendations for the Scottish Government, Zero Waste Scotland and onshore wind industry to enable a more circular approach to onshore wind decommissioning in Scotland to be considered based on the research undertaken. These recommendations include further development of the GVA and carbon calculations, incentivising the growth of supply chain for employing circular processes, and identifying the capacity and optimal location for decommissioning hub(s) at ports based upon the decommissioning forecasts.

1. Introduction

1.1.1 Overview

Jacobs was commissioned by Zero Waste Scotland to quantify the profile of onshore wind decommissioning in Scotland from the present (2021) to 2050 along with an estimate of the materials volumes generated from this activity. The project also seeks to identify circular economy challenges and opportunities for these materials to enable cost effective and sustainable development of the Scottish onshore wind market. In order to do so, seven tasks have been undertaken and which are further detailed in Sections 2-8 of this report:

Task 1 - Decommissioned turbine estimates (Section 2): Recognised datasets of operational, consented and wind farms under construction were used to establish the material arisings and geographical spread of wind turbines across Scotland from present (2021) to 2050.

Task 2 - Circular Economy Options for materials and components (Section 3): Published research as well as analysis carried out as part of market engagement with Scotland's onshore wind sector was used to examine decommissioning treatment options for wind turbines, resulting in a multicriteria assessment (MCA) of the options.

Task 3 - Value of options (Section 4): An initial cost assessment was developed for a typical 2MW wind turbine using an expected disposal route in UK based on current practice as the baseline. Cost assessments were developed for refurbishment, reuse, recycling treatment, and disposal options to identify possibilities to generate revenue. A series of Gross Value Added (GVA) calculations were also developed for decommissioning and treatment options to measure potential wider economic impacts in Scotland.

Task 4 - Carbon Impact (Section 5): An initial carbon footprint was calculated to determine the embodied carbon emissions associated with the manufacturing of wind turbines using virgin materials compared with the embodied carbon content of a wind turbine using materials with recycled content. Transport emissions have also been calculated associated with the movement of material from decommissioned sites to potential locations for a decommissioning hub.

Task 5 - Process of storing and separating materials (Section 6): This identifies the considerations for disassembly, transportation, and separating and storing materials and waste to ensure that these elements from the decommissioning process achieve the best circular economy outcomes.

Task 6 - Opportunities in moving to a circular approach to decommissioning (Section 7): This summarises the considerations that could inform a future guide on decommissioning wind turbines for a circular economy in Scotland drawing on the research undertaken and the findings of the market sector survey and interviews set out in Task 7.

Task 7 - Sector Engagement (Section 8): A market research survey and virtual interviews were completed with wind farm developers, wind farm operators, a wind turbine manufacturer and circular economy businesses to test key aspects of the research undertaken on the previous tasks.

1.1.2 The Opportunity

The potential for a circular economy approach to onshore wind decommissioning offers a strong market opportunity to both fulfil remanufacturing commitments of Making Things Last (The Scottish Government, 2016) and enable further cost effective and sustainable development of the Scottish onshore wind market.

As noted by Welstead et al. (2013), there has been limited experience in the decommissioning of onshore wind farms due to their expected 25 year lifespan with the majority in Scotland constructed from the late 1990s onwards. Since limited published studies exist on the scale of the onshore decommissioning market in Scotland, small-medium sized enterprises (SMEs), operators, and investors often cite that forecasts of materials volumes are a barrier for future planning of the skills and infrastructure needed to develop this market. However, significant circular economy opportunities exist through the reuse, refurbishment and repurposing of components and materials.

Furthermore, previous Zero Waste Scotland estimates found that over £70m could be added to the end-of life asset value of key materials that were in operation in Scotland's renewables sector in 2014 (Amec E&I UK Ltd, 2014). The adoption of a circular economy for decommissioned wind turbines also offers the opportunity to reduce carbon emissions, improve material management, create skills and job opportunities and add value to the Scottish economy.

The Energy Transmission Alliance (2021) report 'Sustainable Decommissioning: Wind Turbine Blade Recycling' sets out the opportunity that exists for the UK supply chain in designing solutions to tackle the recycling challenge and capturing a global market that encompasses 2.5 million tonnes of composites already in use in the wind energy sector. The report outlines that moving turbines towards zero waste will be the next opportunity for the UK supply chain through remanufacturing, reuse, repowering and upgrading of components too. If realised, a spin-off circular economy from offshore wind could extend the current projection of 60,000 jobs in the sector by an additional 20,000 jobs. While these job projections are for offshore wind, the onshore wind sector could also see additional jobs if similar principles are applied to the sector.

The information produced as part of this project will be used to identify and inform future funding priorities and provide an objective market assessment which may stimulate commercial investment in the circular economy.

The sections below detail the distinction between the linear economy and the circular economy, and the challenges faced by the onshore wind sector in applying circular economy principles to decommissioning.

1.1.3 The Circular Economy

The circular economy is defined by the Ellen MacArthur Foundation (2021) as being "based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems." This is the alternative model to the traditional linear economy model which follows the "make, use, dispose" consumption sequence. Within the context of the onshore wind sector, the below diagrams (Figure 1.1 and Figure 1.2) show a comparison between the linear and circular economy and illustrate how the recovery of materials from onshore wind turbines can contribute to the circular economy, reducing the demand for virgin materials and the volume of material sent to landfill.

The benefits that would be realised if the circular economy is applied by the onshore wind sector includes:

1. **Economic impact -** Creation and sale of products from materials that may currently be disposed to landfill or sold abroad. This keeps materials in valuable use for longer, retains value in Scotland, generates additional revenues for the Scottish economy and creates jobs.
2. **Landfill -** Avoid landfill costs for businesses and reduce waste going to landfill.
3. **Carbon impact –** Reduce carbon impact through the recycling of materials that are currently disposed to landfill and which, in the process, displaces virgin materials that require energy intensive processes.

Figure 1.1 illustrates that following a linear model, waste materials arising during construction, operation and decommissioning are either sent to landfill for disposal (red arrows) or sent to waste reprocessing facilities for recycling (yellow arrows). Figure 1.2 illustrates that following a circular model, materials can be reused during construction and at other onshore wind projects and waste can be reduced through design and procurement stages.

At present the relative volume of each of the material flows for onshore wind projects in Scotland is unknown. However, Task 1 (Section 2) identifies what the potential flow would be for decommissioning in based on high and low decommissioning scenarios between 2021 and 2050.

Figure 1.1: The linear approach to materials in the context of an onshore wind project

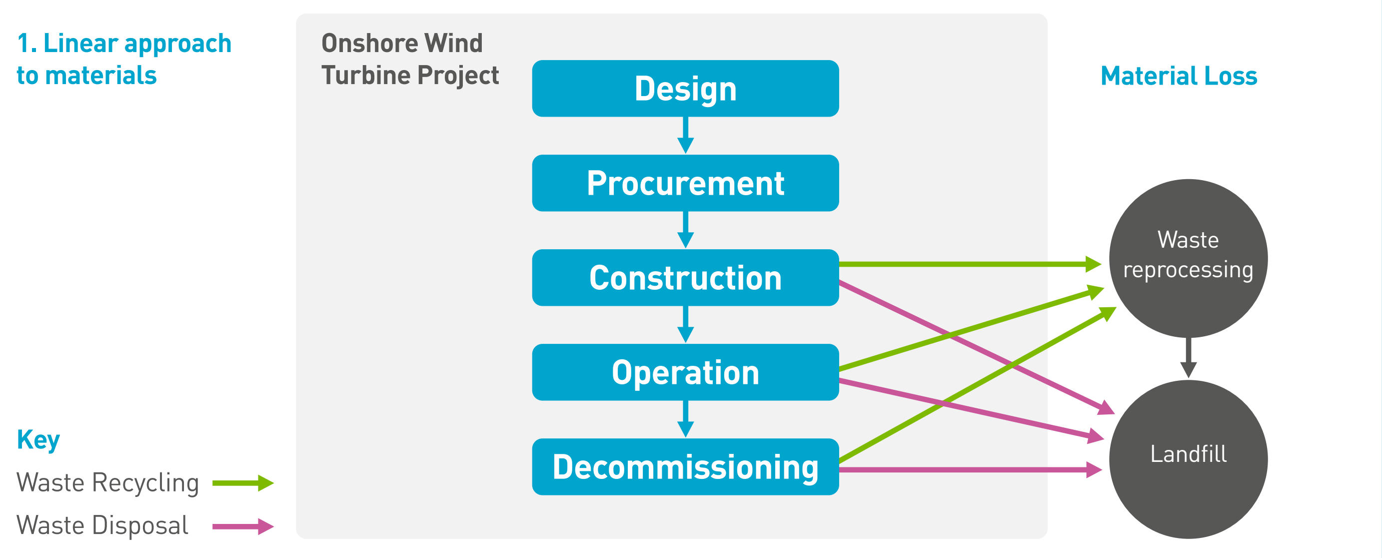
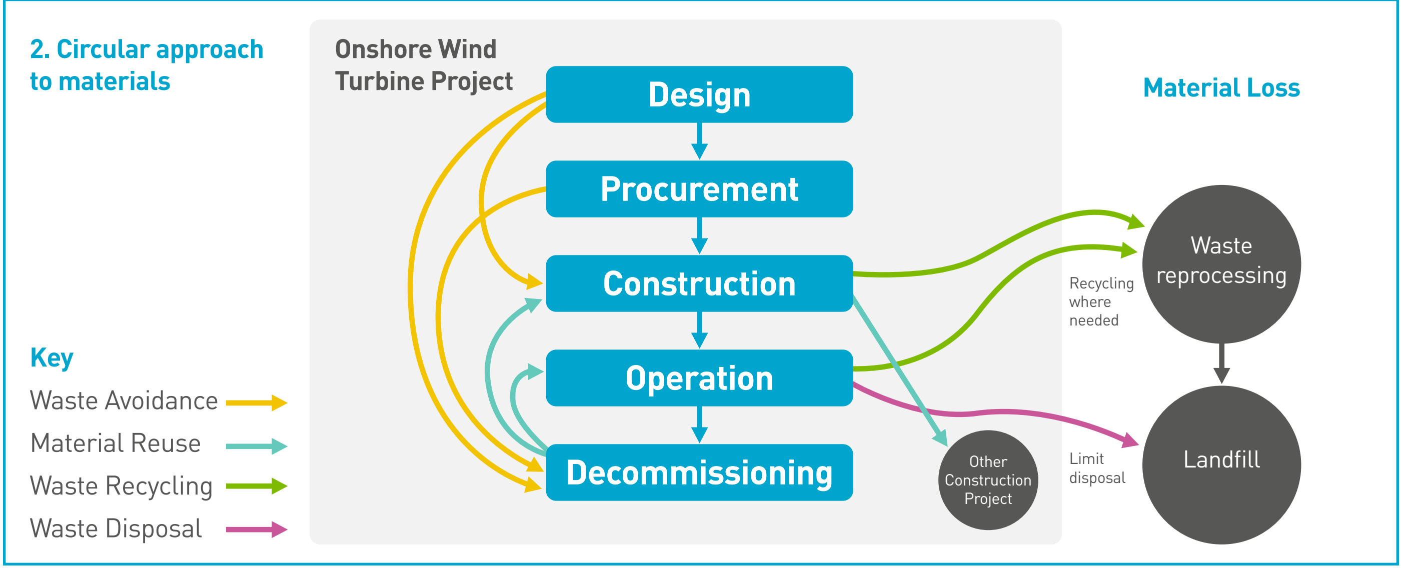


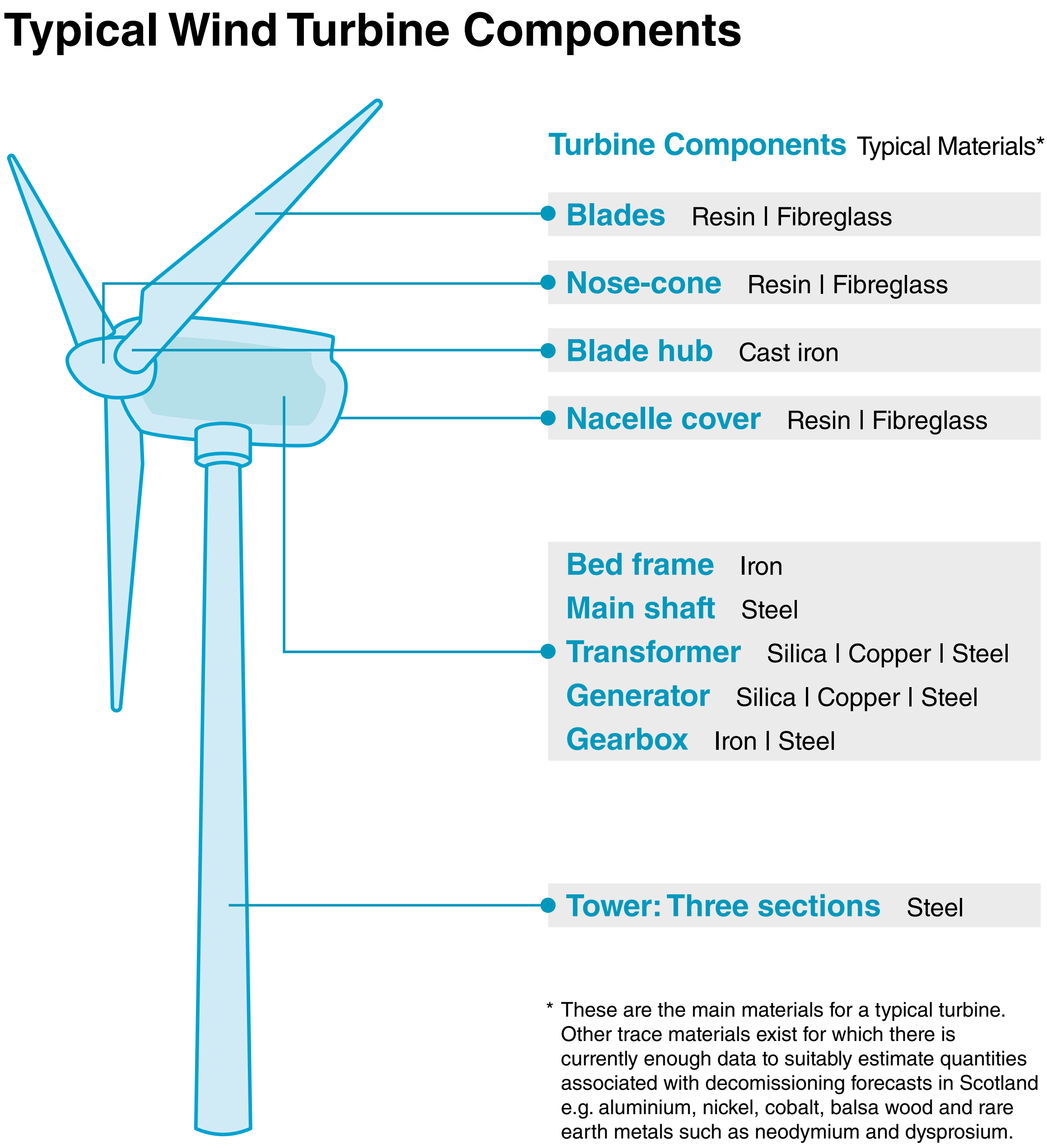
Figure 1.2: The circular approach to materials in the context of an onshore wind project



1.1.4 Challenges for Scotland's Onshore Wind Sector

There are several challenges faced by the onshore wind sector in applying the circular economy. As mentioned in Section 1.1.2, SMEs, operators, and investors often cite that forecasts of materials volumes are a barrier for future planning of the skills and infrastructure needed to develop the market. Barriers to implementing the circular economy also include the difficulty in recycling turbine components. The components that make up a typical onshore turbine are shown in Figure 1.3 and mainly consist of iron, copper, steel, resin and fibreglass although other materials are also included such as aluminium, nickel, cobalt and the rare earth metals neodymium and dysprosium. Applying the circular economy to these components is currently challenging because they include a mix of both recyclable materials such as steel and non-recyclable materials such as fibreglass. Furthermore, there is currently a lack of supply chain and infrastructure in Scotland to process decommissioned wind tubines which is discussed further in Section 3 of the report.

Figure 1.3: The Components of a Typical Wind Turbine



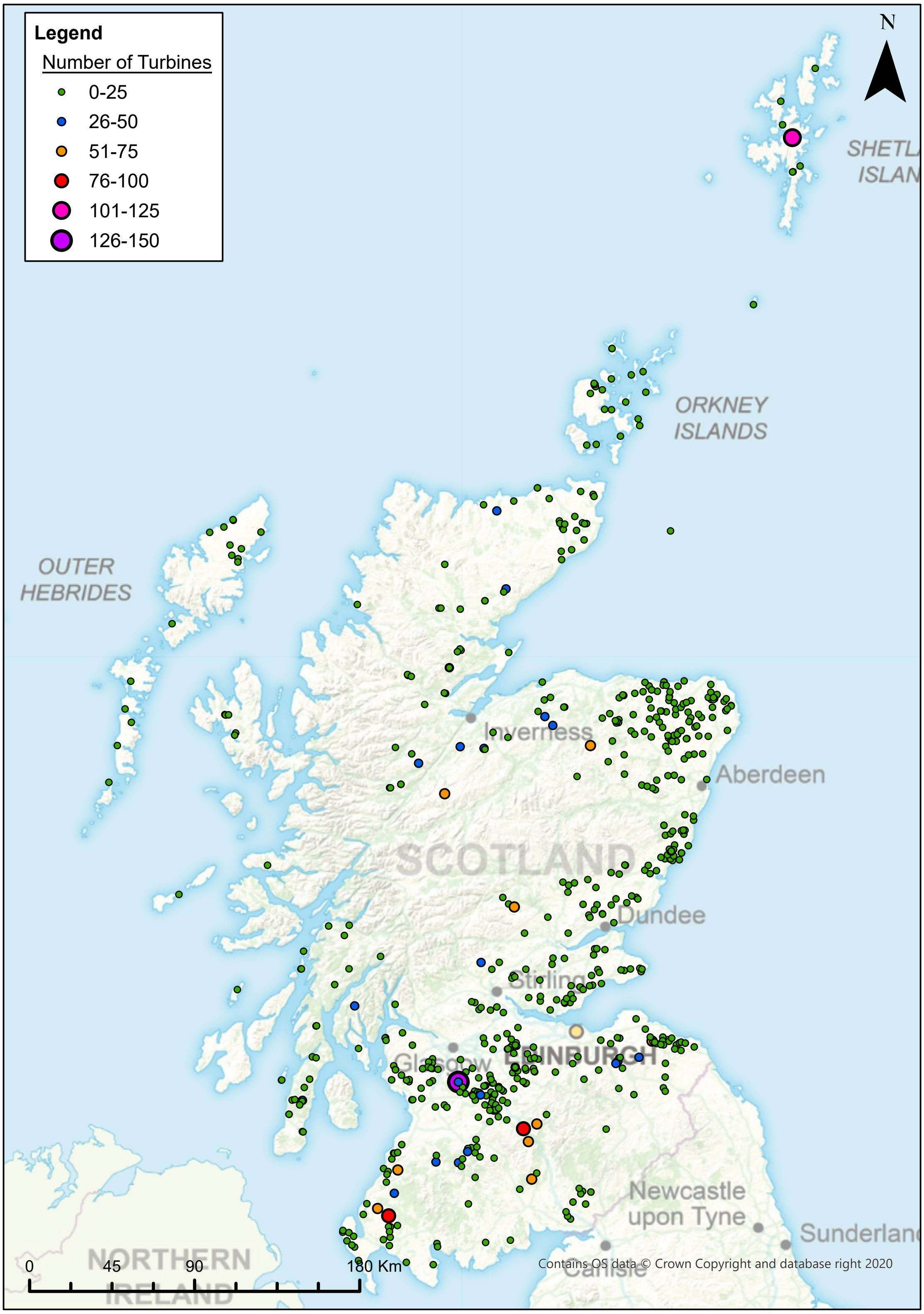
Turbine Components	Typical Materials*
Blades	Resin I Fibreglass
Nose-cone	Resin I Fibreglass
Blade hub	Cast iron
Nacelle cover	Resin I Fibreglass
Bed frame	Iron
Main shaft	Steel
Transformer	Silica I Copper I Steel
Generator	Silica I Copper I Steel
Gearbox	Iron I Steel
Tower: Three sections	Steel

* These are the main materials for a typical turbine. Other trace materials exist for which there is currently enough data to suitably estimate quantities associated with decomissioning forecasts in Scotland e.g. aluminium, nickel, cobalt, balsa wood and rare earth metals such as neodymium and dysprosium.

1.1.5 Geographical Location

The geographic spread of consented, operational and wind farms under constructionin Scotland is shown on Figure 1.4 (based on the Renewable UK (RUK) Database, 2021). This has been used to inform potential decommissioning hub locations for the carbon assessment as presented in Section 5 (Task 4). Each of the seven tasks introduced in Section 1.1 of the report are discussed in the following Sections (Sections 2-8) of this report.

Figure 1.4: Geographic spread of operational and consented wind energy sites in Scotland



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2. Task 1: Decommissioned Turbine Estimates

2.1.1 Methodology

To estimate the number of onshore wind turbines to be decommissioned between 2021 to 2050, a model was created in Microsoft Excel using the RUK Database (2021) which provides information on the UK's operational and consented onshore wind turbines above 100kW.

The model was developed using several assumptions which are listed below:

1. Consented, operational and windfarms under construction are based on the RUK 'Database of Wind Energy Projects in the UK' (Renewable UK, 2021).
2. Any small-scale developments less than 100kW are not included within the RUK data and are therefore not considered within the estimates.
3. Existing turbines on a repowered project will be decommissioned using the low and high repowering forecasts in assumptions 4 and 5.
4. Low decommissioning forecast assumes the following:
    a. 30% of operational turbines are repowered after 20 years;
    b. 20% of operational turbines are repowered after 25 years;
    c. 20% decommissioned after 25 years; and
    d. 30% decommissioned after 35 years.
5. High decommissioning forecast will assume the following:
    a. 25% of operational turbines are repowered after 15 years;
    b. 25% of operational turbines are repowered after 20 years
    c. 25% of operational turbines are repowered after 25 years;
    d. 15% decommissioned after 25 years; and
    e. 10% decommissioned after 35 years.
6. The consent for any projects granted planning permission before 2016 will have expired and a new consent will be required. Therefore, it is assumed that the project will not become operational before 2025 and will be decommissioned after 2050 (based on 25 year lifespan).
7. Projects consented in 2016 or later will become operational 5 years after consent (e.g., consented in 2016, operational in 2021; consented in 2017, operational in 2022 and so on).
8. Any wind turbines consented in 2021 will be operational in 2026 and decommissioned after 2050 (based on 25 year lifespan).
9. The average weights for each category are based the turbine models in the RUK database where information on the total weight is available. The averages are weighted according to the number of turbines of each model in Scotland, based on the models that appear in the RUK 'Database of Wind Energy Projects in the UK'.
10. It is assumed that 81% of the turbine components are recycled (Martínez et al., 2009) (including 90% steel, 90% copper, 95% iron) and 19% will be sent to landfill (including fibreglass, silica & resin). Martínez et al., 2009 was used to calculate the breakdown of materials.
11. It is assumed that the sites listed as "Under construction" in the Renewable UK database will become operational in 2022.

Assumptions 4a-b and 5a-c were initially based on WindEurope (2017) who developed a model to forecast a range for the potential repowering of wind turbines in Europe[1]. The WindEurope model takes into account variation of turbines' lifetimes between 20 and 25 years and relies on "Low repowering" and "High repowering" scenarios as follows:

The "Low repowering" assumes:
- 30% of turbines repowered after 20 years; and
- 20% of turbines repowered after 25 years.

The "High repowering" assumes:
- 50% of turbines repowered after 20 years; and
- 25% of turbines repowered after 25 years.

The WindEurope "Low repowering" assumptions are replicated in assumption 4a-b for this project while "High repowering" was modified following feedback from the market research survey where a wind farm operator noted that they were proposing repowering for some projects between

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[1] Repowering is the process of replacing wind turbines within a windfarm with newer turbines.

10-15 years. The combination of the WindEurope model and market feedback is reflected in assumptions 5a-c for this project.

Assumptions 4c-d and 5d-e are informed by typical planning permissions for wind farms in Scotland being conditioned to 25 years and on the basis that some operators will apply for planning permission for lifetime extension for some sites where some of the components of an existing wind turbine may require to be upgraded (e.g. generator). From the research undertaken as part of this project, there is currently little evidence that wind turbines remain operational beyond 35 years.

Assumption 6 is also informed by planning conditions which typically state that construction works will be required to take place within the specified time period from planning consent. For onshore wind farms, this is typically 3 years and very rarely any more than 5, albeit developers may request extensions in some instances.

Assumptions 7 and 8 are based on an estimated period from planning consent to full operation. This considers the time taken to discharge planning conditions, secure grid connections, procurement of turbines and construction contractors and construct the wind farm. It is recognised that this period will vary considerably depending on the scale and complexity of the development.

Assumption 10 is based on Martinez et al. (2009) which details the materials for a typical 223 tonne 2MW wind turbine, a recycling rate of 81% and a total disposal rate for the components as 19%.

The assumptions were tested by the market research survey, the outcomes of which are summarised in Section 8 of this report. Of the 16 respondents, 12 either had no comments on the assumptions or agreed with them. Two respondents suggested that lifetime extension should be considered, and this is captured in assumptions 4d and 5e. As explained above, feedback on the high decommissioning forecast is captured in assumption 5a. One respondent explained that a previous iteration of assumption 2 was invalid where it was initially proposed that small scale developments with three turbines or less at 0.5MW per turbine were assumed to be non-commercial developments and are not considered within the estimates. This respondent explained that the medium wind market in Scotland is experienced with decommissioning, reuse, refurbishing turbines, repowering sites, and parts replacement and reuse. Therefore, turbines between 100kW and 500kW were included in the forecasts. As noted in assumption 2, turbines with a capacity less than 100kW are not included within the RUK data and are therefore not considered within the estimates.

Four size categories were used to organise the data and were based on a minimum and maximum capacity as shown in Table 2.1 below. A weighted average was calculated for each category so that where there is a higher frequency of one model then it influences the average weight for the category more than a lower frequency of another model. This avoids anomalies (e.g. a particularly heavy or light turbine model where only small numbers in Scotland exist) impacting the average weights for each category. It is noted that the RUK database does not include details of the turbine models for all sites and therefore there are unknown turbine models. Also, it is difficult to determine turbine model weights and so the weighted average is based on the information that is available online. The weights for the turbine models were predominantly taken from an online database called 'Wind Turbine Models' (2021), however, if this did not include the model weights other sources were used such as 'The Wind Power' (2021). Obtaining more weights for the models in Scotland and their breakdown by material is an area for development in the model.

Table 2.2 outlines the turbine models that the average weight for each category is based on.

Table 2.1: The model categories organised by turbine capacity

Turbine category	Minimum capacity (MW)	Maximum capacity (MW)	Weighted Average (tonnes)
S	0.1	0.5	31
A	0.5	2	105
B	2	3	293
C	3	5	475

Table 2.2: The turbine models used to calculate the turbine categories average weight

Turbine category	Average weight, tonnes	Models the average is based on
S	31	ACSA A27; Turbowind T400-34; Vestas V27; WTN 250.
A	105	Gamesa G87; GE 1.6; NM1100-600; Nordex N60; Vestas V80; Vestas V90.
B	293	Bonus B82/2300; Nordex N80; Siemens 2.3; Siemens SWT-2.3-82; Siemens SWT-3.0-101.
C	475	Siemens SWT-3.6-107.

To calculate the average weight of the various materials of the wind turbine and the recycling and disposal rates, information was taken from Martinez et al. (2009) which details the materials for a typical 223 tonne 2MW wind turbine. Based on Martinez et al. (2009), the recycling rate is 81% and the total disposal rate for the components is 19%. These rates were applied to the capacity size categories to calculate the average weight of material to be recycled versus being disposed of (Table 2.3). The components of a turbine as detailed in Martinez et al. (2009) were also used to calculate the volume of each material that is typically recycled or disposed of. These volumes are shown in Table 2.4.

Table 2.3: The average weight (in tonnes) to landfill and the average weight to be recycled based on current disposal and recycling methods

Turbine category	Capacity Range (MW)	Average weight to landfill (tonnes)	Average weight to recycle (tonnes)
S	0.1 – 0.5	6	25
A	0.5 – 2	20	85
B	2 – 3	56	238
C	3 +	90	385

Table 2.4: The average weight (in tonnes) of the main turbine materials typically recycled or sent to landfill

Turbine category	Capacity Range (MW)	Copper to be recycled	Iron to be recycled	Steel to be recycled	Fibreglass to landfill	Resin to landfill	Silica to landfill
S	0.1 – 0.5	0.47	2.78	22.13	1.22	1.84	0.10
A	0.5 – 2	1.57	9.35	74.49	4.12	6.18	0.33
B	2 – 3	4.37	26.00	207.04	11.45	17.17	0.92
C	3+	7.08	42.14	335.56	18.56	27.84	1.49

2.1.2 Model Forecasts

The model includes two estimates for decommissioned onshore wind turbines from 2021 to 2050 covering a low decommissioning forecast and a high decommissioning forecast based on assumptions 4 and 5 set out in Section 2.1.1 using the RUK 'Database of Wind Energy Projects' in the Scotland and the four turbine categories.

The key outputs from the two models are shown below in Table 2.5.

Table 2.5: Key outputs from the low and high decommissioning forecasts

Model	Total number of turbines decommissioned from 2021-2050	Total weight of material forecast by 2050 (tonnes)
Low decommissioning forecast	4,894	1,238,344
High decommissioning forecast	5,613	1,459,045

In both the low and high decommissioning forecasts the largest volume of onshore wind turbines for decommissioning from present to 2050 come from category B wind turbines (2-3MW) (Figures 2.1 and 2.2). From the modelling forecasts, there are projected annual peaks of decommissioning which may arise from a number of large sites being decommissioned in these years (in addition to other sites with smaller capacities). For example, the two biggest annual projected peaks for the low decommissioning forecast in 2037 and 2042, shown in Figure 2.1, may arise in years when the following sites may influence the forecasts:

- 2037:
    - Scottish Power Renewables: 38 turbines at Whitelee.
    - SSE Renewables: 68 turbines at Griffin, 96 at Clyde (North and Central) and 35 turbines at Gordonbush.
- 2042:
    - Scottish Power Renewables: 96 turbines at Kilgallioch and 35 turbines at Hare Hill Extension.
    - SSE Renewables: 54 turbines at Clyde Extension and 33 turbines at Dunmaglass.

This illustrates that the decisions made by a small number of operators including Scottish Power Renewables and SSE Renewables significantly influence the timing of material flows arising from decommissioning. Given the nature of the factors that influence decommissioning and/or repowering a site it is very likely that these decisions may change at short notice. For example, the timing of securing grid connection or award of a Contracts for Difference auction may accelerate or decelerate the timing of decommissioning. This is illustrated when comparing Figure 2.1 and Figure 2.2 where the high forecast which assumes earlier, and more repowering accelerates the material flow towards 2021 while the low forecast which assumes lower and later repowering delays the material flow towards 2050.

Figure 2.1: Decommissioned onshore wind turbine estimates by category for low decommissioning forecast

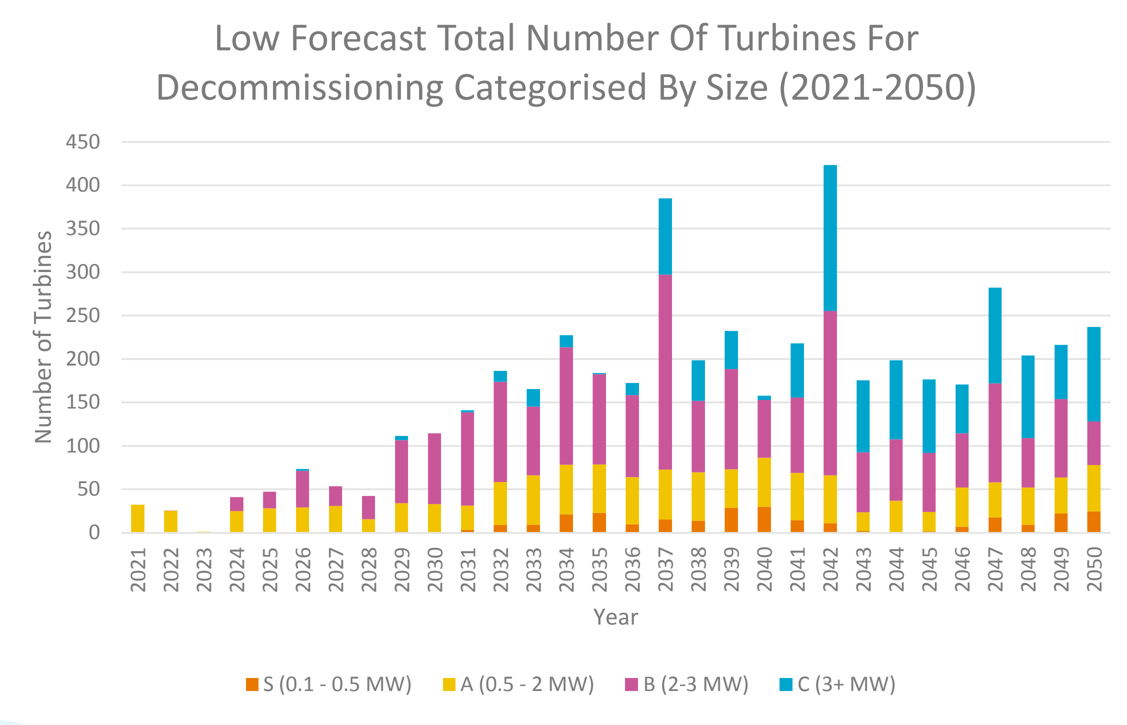
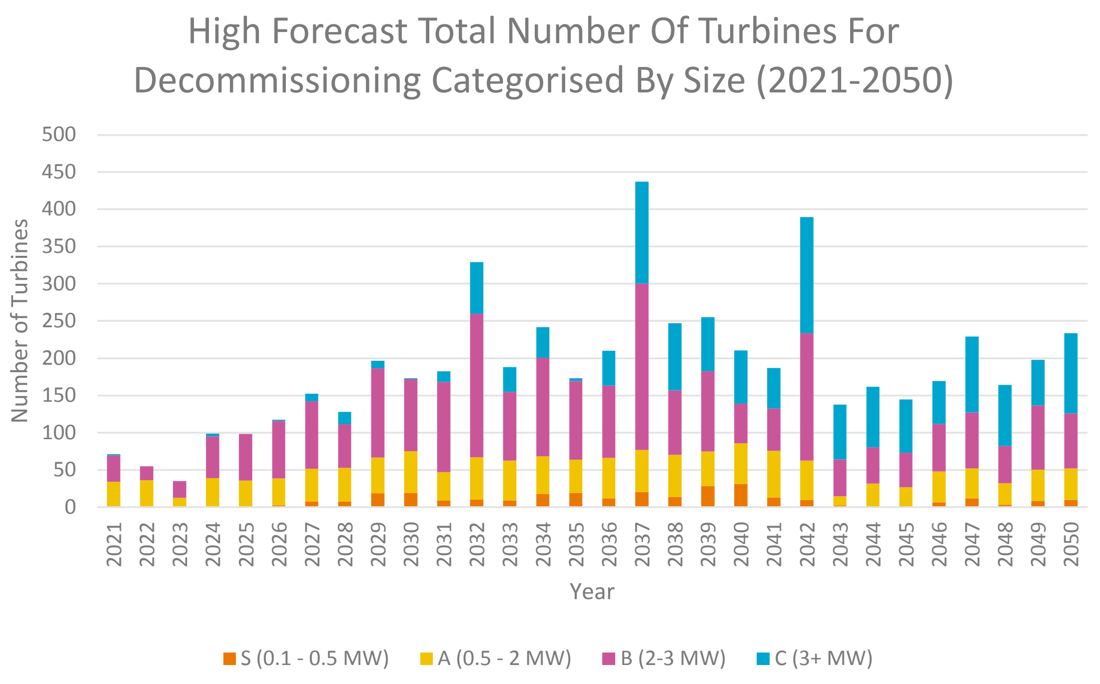


Figure 2.2: Decommissioned onshore wind turbine estimates by category for high decommissioning forecast



Additionally, the total weight of key materials flows from decommissioning turbines was calculated for both the low forecast decommissioning and the high forecast decommissioning as shown in Table 2.6 below and illustrated in Figure 2.3 and Figure 2.4 over the page.

Table 2.6: Material available from the low and high decommissioning forecasts

	Total weight of material forecast by 2050 (tonnes)				
Model	**Iron**	**Steel**	**Copper**	**Fibreglass**	**Resin**
Low decommissioning forecast	120,137	956,728	20,175	52,909	79,363
High decommissioning forecast	141,594	1,127,602	23,778	62,359	93,538

Figure 2.3: The total volume of material estimated by 2050 from the low decommissioning forecast

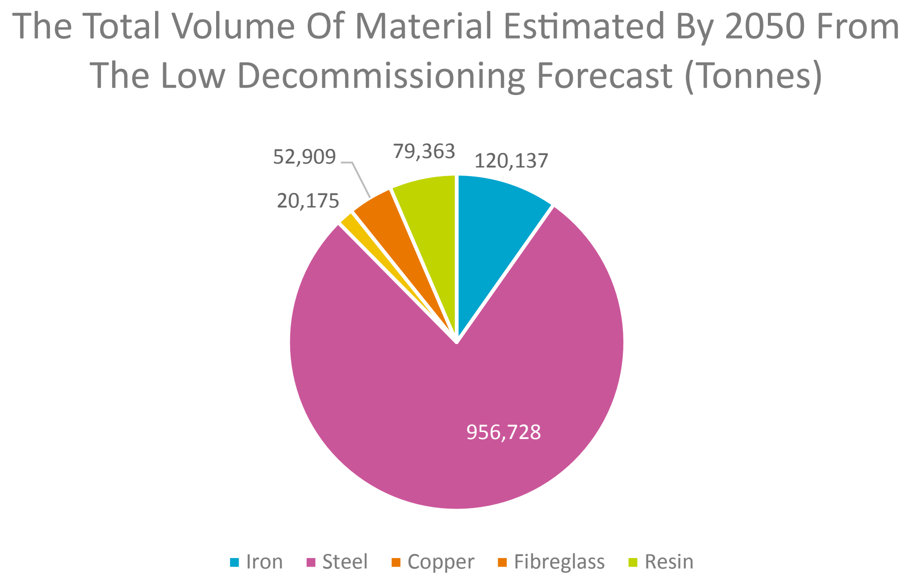


Figure 2.4: The total volume of material estimated by 2050 from the high decommissioning forecast

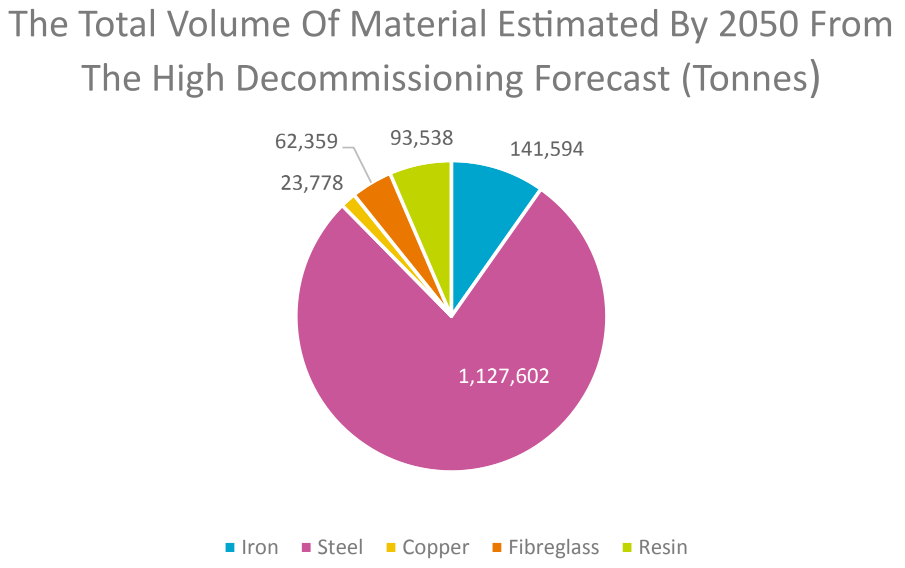


Figure 2.5 and Figure 2.6 illustrate the cumulative volume of material generation over time that would result from onshore wind decommissioning in Scotland for the low and high forecasts respectively.

Figure 2.5: Cumulative Volume of Materials for the Low Decommissioning Forecast

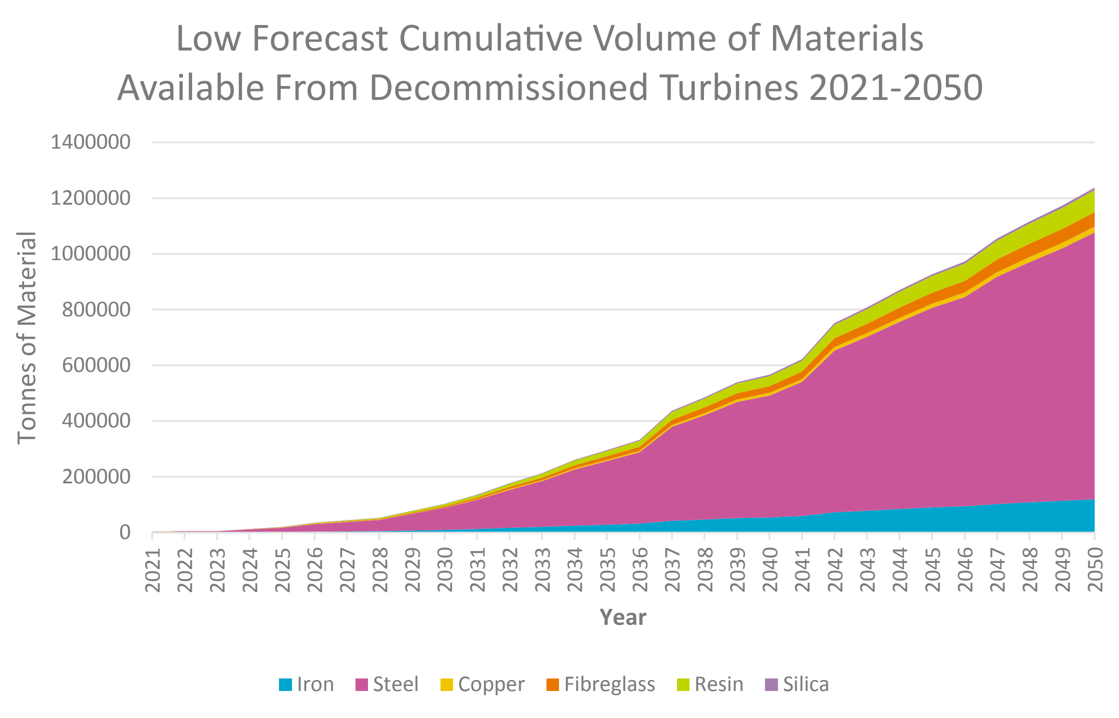
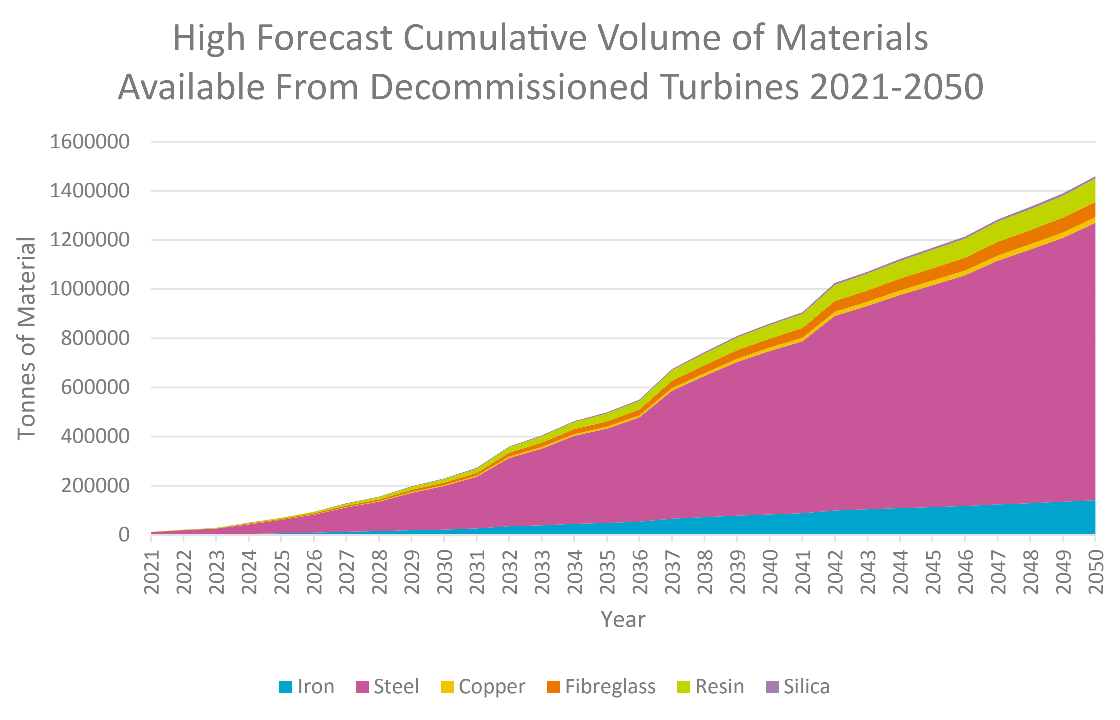


Figure 2.6: Cumulative Volume of Materials Available From Decommissioned Turbines Between 2021-2050 For the High Forecast Model



3. Task 2: Circular Economy Options for Materials and Components

3.1.1 Methodology

Treatment options have been identified, described, and evaluated as part of the assessment of applicable circular economy-based solutions for decommissioned onshore wind turbines. The assessment has applied assumptions on components and material composition described in the inventory in Table 1 of Martinez et al. (2009) which was also used to model the decommissioning forecasts set out in Task 1 (Section 2). Treatment options have been assessed using a multi-criteria assessment (MCA) to test and confirm preferred management routes and best practice, validating capacity issues that may constrain a treatment option in Scotland. As a number of treatment options exist, they have been ranked to indicate a hierarchy of preference to inform future practice.

The assessment draws on published research, analysis carried out as part of Jacobs' internal market analysis, work on projects delivered through Zero Waste Scotland's Circular Economy Business Support Service, and engagement with the onshore wind sector described in Section 8 of this report.

3.1.1.1 Treatment Options

The treatment of onshore wind turbines has been applied in three forms:

- full turbine;
- component parts; and
- individual materials.

Table 3.1 describes the treatment options applicable to these three forms, providing a brief description of the process itself and the expected output from the treatment process. The treatment options described in Table 3.1 provide the basis of the MCA in Table 3.2.

3.1.1.2 MCA

An MCA methodology has been developed to guide the assessment of 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. It introduces a focus on circular economy principles identified in the 'Making Things Last: A Circular Economy Strategy for Scotland', (The Scottish Government, 2016), which refers to The Ellen MacArthur Foundation concept. Table 3.2 sets out the MCA scoring methodology, while Table 3.3 details reference materials and base assumptions applied when assessing the treatment options; the MCA results are set out in Figure 3.1 and Table 3.4.

The output from the MCA is an average of the MCA category scores for each treatment option assessed against a full turbine, component, or individual material. With eleven unweighted categories, the assessment produces a thorough review of the impacts of decommissioning.

3.1.2 Limitations

As decommissioning within Scotland's onshore wind industry is not yet well established, it is necessary to acknowledge the limitations in the availability of published literature and data. Table 3.3 summarises this information and the resulting base assumptions have been applied to create the MCA methodology and further assumptions applied during the application of MCA methodology to the treatment options in Table 3.4.

Table 3.1: Onshore wind Turbine Treatment options

Treatment options	Description	Output from treatment	Example reference
FULL TURBINE			
Life extension	Maintenance of turbine to extend life and delay decommissioning.	Extend life of existing turbine	Zero Waste Scotland (2019) Sayer (2009) Scottish Natural Heritage (2013) Re-wind (2021) Electric Power Research Institute (2018)
Refurbishment of full turbine	Decommission turbine, recondition the full unit to extend life for reinstallation at a new location.	Extend life of existing turbine following decommissioning	Zero Waste Scotland (2019) Sayer (2009) Scottish Natural Heritage (2013) Re-wind (2021) Electric Power Research Institute (2018)
COMPONENTS			
Refurbishment	Refurbish component parts for direct reuse on different wind turbines. Refurbishment would require certification for safe implementation.	• Refurbish parts of turbines and refurbish for maintenance on others. • Extend life of turbines	Zero Waste Scotland (2019) Sayer (2009) Scottish Natural Heritage (2013)
Reuse of components in new structure	Repurpose the component for novel or bespoke use as a mechanical or structural element. Reuse would likely require checks and certification for secure implementation.	• Reefs • Bridges • Electricity transmission towers • Wake breaks • Playground equipment • Public benches • Signage • Motorway sound barriers	Zero Waste Scotland (2019) Re-wind (2021) Electric Power Research Institute (2018) Scottish Natural Heritage (2013)
MATERIALS			
Material recycling: Scrap metal recycling	Recycling scrap steel through traditional methods such as processing through furnaces.	• Metal repurposed	Scottish Natural Heritage (2013) Electric Power Research Institute (2018)
Electric arc furnace recycling	Recycling scrap steel via a furnace that heats charged material by means of an electric arc.	• Metal repurposed • Surplus slag for construction aggregate	Amec E&I UK Ltd (2014)

Table 3.1: Onshore wind Turbine Treatment options

Treatment options	Description	Output from treatment	Example reference
Mechanical recycling for construction	Shredding and grinding followed by screening to separate fibre-rich and resin-rich fractions for reuse. Water jet cutting, wire saw cutting, circular jaw cutting, or use of jaw cutters.	• Precast concrete • Construction sandwich panels • Cement feedstock • Precast manholes • New jersey barriers • Lego type concrete blocks	Life Brio (2017) Veolia (2020) Zero Waste Scotland (2019) Electric Power Research Institute (2018)
Pyrolysis	Dry distillation process to turn fibreglass (composite) waste into two fractions.	• Oil/gases to produce thermal energy • Fibre for filler	Scottish Natural Heritage (2013) Psomopoulos et al (2019) Electric Power Research Institute (2018)
Chemical depolymerisation (Solvolysis)	Removal of the matrix and liberation of fibres for further recycling by using organic or inorganic solvent.		
Thermal processing	Thermal processing uses high temperature (between 300 and 1000 °C) to decompose resin and separate the reinforcement fibres and fillers.	• Clean fibres • Inorganic fillers	Scottish Natural Heritage (2013) Electric Power Research Institute (2018)
Energy recovery	Incineration of the material to recover waste as energy.	• Energy production • Ash cement filler	Amec E&I UK Ltd (2014) Psomopoulos et al (2019)
Landfill	Disposal of the entire turbine or components in traditional inert, non-hazardous, or hazardous landfill sites.		

Table 3.2: MCA methodology

		MCA Score				
Category	**Description**	**1**	**2**	**3**	**4**	**5**
Cost/Value	Cost/Value generation per tonne from implementing treatment process for a typical 2MW Turbine.	Treatment process generates cost > £500 per tonne.	Treatment process generates cost < £500 per tonne.	Treatment process is cost neutral cost per tonne.	Treatment process generates revenue < £500 per tonne.	Treatment process generates revenue > £500 per tonne.
Resource efficiency	Based on the Ellen MacArthur Foundation Circular Economy System Diagram, identifying the degree of efficiency through using circular economy processes.	Materials sent to landfill (Waste)	Waste to energy (Recycle Energy)	Materials reprocessed for alternative use (Recycle)	Reuse of parts for new use (Reuse/ Redistribute)	Refurbishment of turbine (Maintain/ Prolong)

Table 3.2: MCA methodology

Category	Description	1	2	3	4	5
Value retention in Scotland	Material and energy retained within the Scottish economy against the total raw material (Ellen MacArthur Foundation).	Below 25% of retained value located in Scotland.	Between 25-50% of retained value located in Scotland.	50% of retained value located in Scotland.	Between 50-75% of retained value located in Scotland.	Over 75% of retained value located in Scotland.
Demand for output	Demand for material product / output from material treatment process.	No demand for the product/output arising from the process exists in Scotland.	Demand for the product/output arising from the process is limited, and considerable effort is required to develop a market.	Demand for the product/output arising from the process is growing, but market development is necessary.	Demand for product/ output arising from the process is growing, minimal market development is necessary.	The product/output arising from the process has an established market in Scotland.
Availability of infrastructure	Availability of infrastructure to accommodate the treatment of materials, considering the investment required within Scotland	No infrastructure exists in Scotland to implement the process.	Limited infrastructure exists in Scotland to implement the process.	The process is growing in Scotland with infrastructure to support; market development is necessary.	The process is growing in Scotland with infrastructure to support; minimal market development is necessary.	The process is well established in Scotland with ample infrastructure to support.
Scalability	Ability for the infrastructure / markets to respond to increased demand for material treatment process. Complexity to develop the market.	Hard to increase scale: • Existing infrastructure / depot cannot accommodate increase in demand through decommissioning. • Current processes and capacity do not allow for adaptation of production.	Moderate to hard scope to increase scale: • Multiple new infrastructure / depots required to accommodate increase in demand through decommissioning. • Little flexibility or capacity exists to adapt production.	Moderate scope to increase scale: • New infrastructure / depot required to accommodate increase in demand through decommissioning. • Some flexibility and capacity exists to adapt production.	Moderate-Easy scope to increase scale: • Existing infrastructure / depot requires modification to accommodate increase in demand through decommissioning. • Flexibility and capacity exists to adapt production.	Easy to increase scale: • Existing infrastructure / depot can accommodate increase in demand through decommissioning. • High flexibility and capacity exists to adapt production.
Carbon intensity	Carbon intensity of material treatment process: tCO_2e per tonne (Based upon carbon modelling).	> 4 tCO_2e per tonne	3.9-3 tCO_2e per tonne	2.9-2 tCO_2e per tonne	1.9-1 tCO_2e per tonne	0.9-0 tCO_2e per tonne

Table 3.2: MCA methodology

Category	Description	1	2	3	4	5
Additional employment generated	Employment generated through material treatment process (in Scotland) assuming decommissioning hub develops existing conditions, infrastructure, and technological availability. Assessed in terms of full time equivalent (FTE).	Expansion of decommissioning is expected to result in a net loss of FTE jobs due to process.	No net loss or gain of employment expected.	Expansion of decommissioning is expected to result in a small net gain of FTE jobs per year.	Expansion of decommissioning is expected to result in a moderate net gain of FTE jobs per year.	Expansion of decommissioning is expected to result in a significant net gain of FTE jobs per year.
Gross Added Value (GVA)	Gross value added of the decommissioning and disposal process.	< 66K per 2MW turbine.	Approx. £66k-68k per 2MW turbine.	Approx. £69k per 2MW turbine.	Approx. £70 - 72K per 2MW turbine.	> 72K per 2MW turbine.
Survey results (current practice)	Onshore Wind Decommissioning Survey Question 2 - Circular Economy options.	Lowest Ranked		Median score		Top ranked
Survey results (opportunities)	Onshore Wind Decommissioning Survey Question 3 - Circular Economy options.	Lowest Ranked		Median score		Top ranked

Table 3.3: MCA assumptions and limitations

Category	Data Source / References	Assumptions and limitations
Cost/Value	Ricardo (2017) Zero Waste Scotland's Circular Economy Business Support Service WRAP (2019) Letsrecycle.com (2021) Renewable Parts Interview (2021) Vestas Interview (2021) Spares in Motion Interview (2021) Scottish Power Renewables Interview (2021) SSE Renewables Interview (2021) Jacobs Wind Solutions Interview (2021)	• Value to operator of refurbished full wind turbine - $150,000 / £107,000 per MW[2]. • Component '£ per tonne' estimated based on estimates from interviews. • Costs to the owner for mechanical treatment will be at least equivalent to disposal. • Thermal processes and energy recovery will push cost of treatment onto operator. • No demand exists for reuse of blades on wind turbines in Scotland, based on interview responses. • No available data for 'reuse within new structure' so assessment made based upon research on available solutions outlined in Table 3.1. • Material values and disposal costs based on Letsrecycle.com Jan 2021 data.
Resource efficiency	The Ellen MacArthur Foundation	n/a
Value retention in Scotland	Zero Waste Scotland's Circular Economy Business Support Service Sayer (2009) Scottish Natural Heritage (NatureScot; 2013) Re-wind (2021) Electric Power Research Institute (2018) Amec E&I UK Ltd, 2014 Life Brio (2017) Veolia (2020) Psomopoulos et al (2019) Renewable Parts Interview (2021) Vestas Interview (2021) Spares in Motion Interview (2021) Scottish Power Renewables Interview (2021) SSE Renewables Interview (2021) Jacobs Wind Solutions Interview (2021)	• Market exists for refurbishing of Scottish onshore and offshore components. Take back schemes and increased supply could cause uncertainties in this market. • Planning conditions, economic benefits and limited infrastructure/facilities leads to the assumption that refurbished full turbines would be unlikely to remain in Scotland. • No demand exists for reuse of blades on wind turbines in Scotland so value retention low • No available data for 'reuse within new structure' so assessment made based upon research on available solutions. • Approx. 40% of recycled scrap metal remains in the UK. • Energy recovery retains less than 25% of material value. • Landfill retains no value.

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[2] Taken from projects undertaken as part of Zero Waste Scotland Circular Economy Business Support and verified during interviews

Table 3.3: MCA assumptions and limitations

Category	Data Source / References	Assumptions and limitations
Demand for output	Zero Waste Scotland's Circular Economy Business Support Service Sayer (2009) Scottish Natural Heritage (2013) Re-wind (2021) Electric Power Research Institute (2018) Amec E&I UK Ltd, 2014 Life Brio (2017) Veolia (2020) Psomopoulos et al (2019) Onshore Wind Decommissioning Survey (Task 7) NREL (2015) Renewable Parts Interview (2021) Vestas Interview (2021) Spares in Motion Interview (2021) Scottish Power Renewables Interview (2021) SSE Renewables Interview (2021) Jacobs Wind Solutions Interview (2021)	• Market exists for refurbishing of Scottish onshore and offshore components. Take back schemes and increased supply could cause uncertainties in this market. • Planning, economic restrictions and examples of refurbished full turbines leads to an assumption of limited demand in Scotland. • No demand exists for reuse of blades on wind turbines in Scotland due to concerns over quality and lifespan. • High industry demand for replacements of electrical/mechanical components like generators, gear boxes and transformers mean demand is established and can be applied to 'refurbishment' and 'reuse within a new structure.' • No available data for 'reuse within new structure' so assessment made based upon research on available solutions. No established solutions for many components (canopy, nacelle cover, bed frame, and blade hub). • Recycled scrap metal is in high demand in the UK and globally. • There is demand for the output of mechanical recycling, pyrolysis, and thermal processing but not from wind turbines. Such feedstock can be obtained with more ease from other sources. • Energy recovery retains less than 25% of material value. • No demand for landfill.
Availability of infrastructure	Zero Waste Scotland's Circular Economy Business Support Service Sayer (2009) Scottish Natural Heritage (NatureScot, 2013) Re-wind (2021) Electric Power Research Institute (2018) Amec E&I UK Ltd, 2014 Life Brio (2017) Veolia (2020) Psomopoulos et al (2019) Onshore Wind Decommissioning Survey (Task 7) Renewable Parts Interview (2021) Vestas Interview (2021) Spares in Motion Interview (2021) Scottish Power Renewables Interview (2021) SSE Renewables Interview (2021) Jacobs Wind Solutions Interview (2021)	• No decommissioning hubs exist in Scotland or the UK. • No electric arc furnaces exist in Scotland. • No mechanical recycling facilities exist in Scotland or the UK. • No pyrolysis/chemical depolymerisation facilities equipped to deal with fibreglass exist in Scotland or the UK. • No thermal processing facilities equipped to process fibreglass exist in Scotland and the UK. • A potential shortage of cranes and transport vehicles exists in Scotland and the UK. • The lower rates of onshore wind farm commissioning could result in skills shortages for decommissioning. Offshore wind turbine may have skilled personnel, but offshore wind turbine commissioning will increase demand for skills further. • Landfill and energy recovery facilities exist but no mechanical shredders with capacity for fibreglass components of an onshore wind turbine exist in Scotland or the UK. • Limited tier 1, 2 and 3 supply chain exist in Scotland, reducing the capacity for refurbishment and reuse.

Table 3.3: MCA assumptions and limitations

Category	Data Source / References	Assumptions and limitations
Scalability	Renewable Parts Interview (2021) Vestas Interview (2021) Spares in Motion Interview (2021) Scottish Power Renewables Interview (2021) SSE Renewables Interview (2021) Jacobs Wind Solutions Interview (2021) Onshore Wind Decommissioning Survey (Task 7)	• Refurbishment of full turbines would require creation of a new decommissioning hub/dept. • Employment skillset required for use of components in new structures is unknown due to uncertainties of their application. However, electrical/mechanical components like generators, gear boxes and transformers are assumed to be scalable as complementary industries already exist in Scotland. • Current scrap metal recycling, energy recovery and landfill scalability is sufficient but restricted by access to mechanical shredders, cranes, and transportation.
Carbon intensity	Carbon Model (Task 4)	• Refer to assumptions of carbon model presented in Section 5 of the report.
Additional employment generated	IRENA (2017) ONS (2019) Ricardo (2017) Renewable Parts Interview (2021)	• Refurbishment and reuse would generate high skilled employment in tier 2 and 3 suppliers from adjacent industries; also resulting in higher GVA gains compared with other treatment processes. • Uncertainty over the reuse of components in novel structures results in lower certainty of employment benefits. • Novel recycling of fibreglass would require new facilities and labour in Scotland, but the quantities of waste from onshore wind would be relatively minor, resulting in less significant employment gains. • Metal recycling, energy recovery and landfill treatment processes have established facilities and labour; therefore, they would receive increased supply of materials with onshore wind using existing capacity and therefore employment benefits are limited. • This does not account for jobs created through disassembly and transport that will occur in all treatment processes.
GVA	IRENA (2017) Scottish Annual Business Statistics (2018) Ricardo (2017)	• Refer to GVA per turbine in Task 3 (Section 4 of this report). • GVA added represents the decommissioning and disposal processes only. • The GVA calculation does not account for value added in future recommissioning, operation and maintenance of the turbines, components, or materials.
Survey results (current practice)	Onshore Wind Decommissioning Survey (Task 7)	• Life extension was not part of survey question due to evolution of the project treatment options. Therefore, based upon interview responses, life extension has been granted joint highest rank. • Landfill was not part of survey question due to evolution of the project treatment options. • As landfill is not a circular economy-based solution, it has been granted joint lowest rank.
Survey results (opportunities)	Onshore Wind Decommissioning Survey (Task 7)	• Life extension was not part of survey question due to evolution of the project treatment options. Therefore, based upon interview responses, life extension has been granted joint highest rank. • Landfill was not part of survey question due to evolution of the project treatment options. • As landfill is not a circular economy-based solution, it has been granted joint lowest rank.

3.1.3 MCA Results

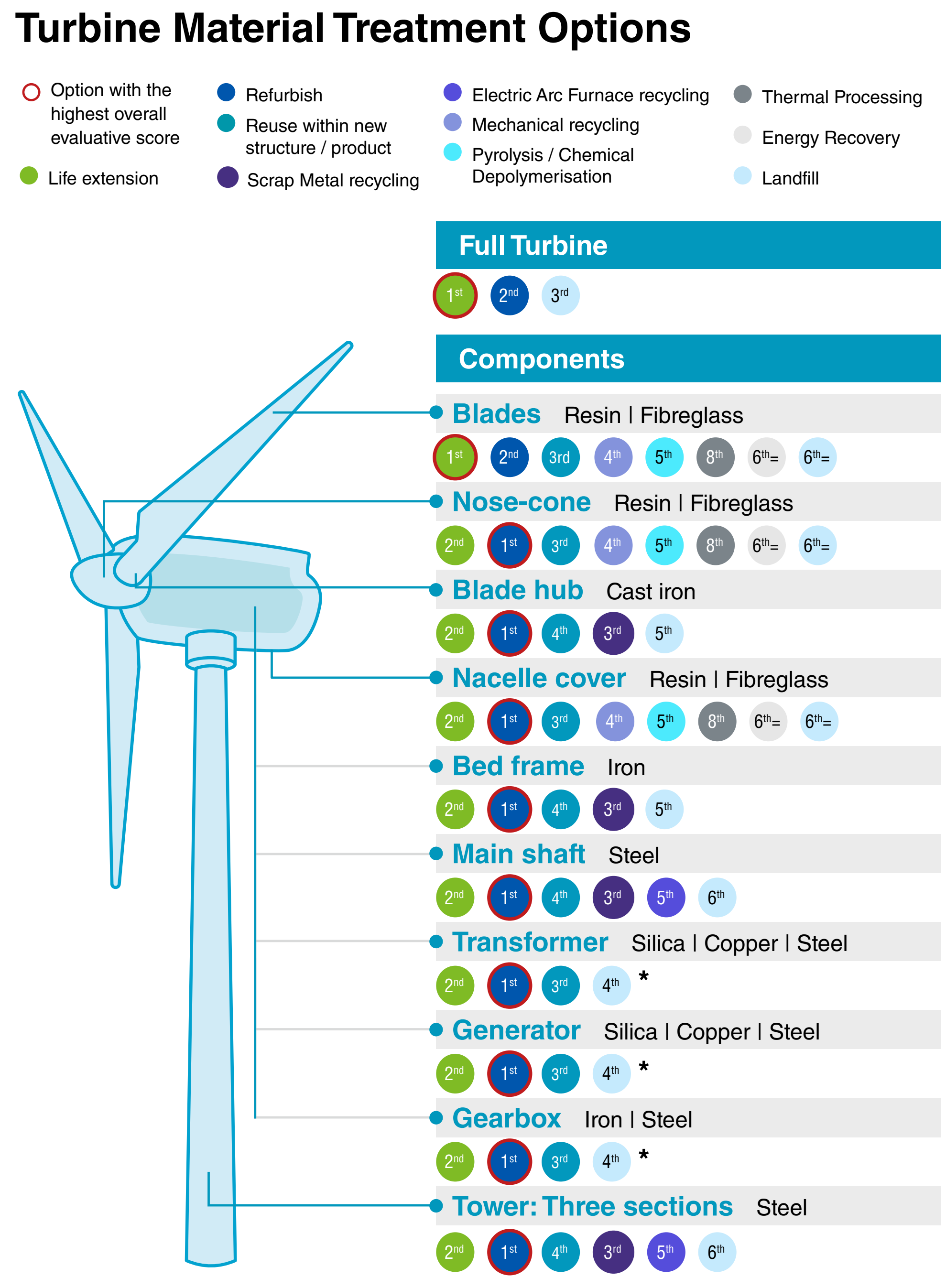
The onshore wind turbine decommissioning treatment options have been ranked based on the MCA methodology. The ranking represents the order of their MCA scoring output.

The ranking results have been displayed according to the three forms introduced in Section 3.1.1: full turbines, components, and individual materials.

Figure 3.1 displays the ranked output of the MCA for full turbines and components. Within each component, recycling options have been ranked if a component consists of one material. Where the component consists of multiple materials (i.e., the transformer, generator, and gearbox) material recycling options are not represented but are set out in Table 3.4 which displays the ranked output of the MCA for materials.

The MCA scoring outputs are represented by ranking, but full scores are available to view in Appendix 1. The MCA scoring outputs can appear close in nature due to the scoring range of 1-5 and often as a reflection the market conditions in Scotland where interdependencies exist between the different treatment options.

Figure 3.1: Onshore Wind Turbine decommissioning treatment MCA analysis for full turbine and components



*Transformers generators and gearboxes consist of multiple components and materials that cannot be processed as one, therefore recycling options are not addressed in the infographic. The treatment methods for materials within these components are addressed in Table 3.4.

Table 3.4: Matrix of materials treatment methods and MCA ranking

	Treatment options						
Materials	**Scrap metal recycling**	**Electric arc furnace recycling**	**Mechanical recycling**	**Pyrolysis / chemical depolymerisation**	**Thermal processing**	**Energy recovery**	**Landfill**
Resin / Fibreglass	-	-	1st	2nd	5th	3rd	3rd
Steel	1st	2nd	-	-	-	-	3rd
Cast iron	1st	-	-	-	-	-	2nd
Iron	1st	-	-	-	-	-	2nd
Copper	1st	-	-	-	-	-	2nd
Silica	-	-	1st	-	-	-	2nd

Figure 3.2 and Figure 3.3 show the survey results for most practical solutions and greatest opportunities for the industry. These results were incorporated into the MCA itself, but also broadly align with the MCA output.

Figure 3.2: Most practical treatment solutions for onshore wind turbines based on survey responses (thermal processing received a score of 0)

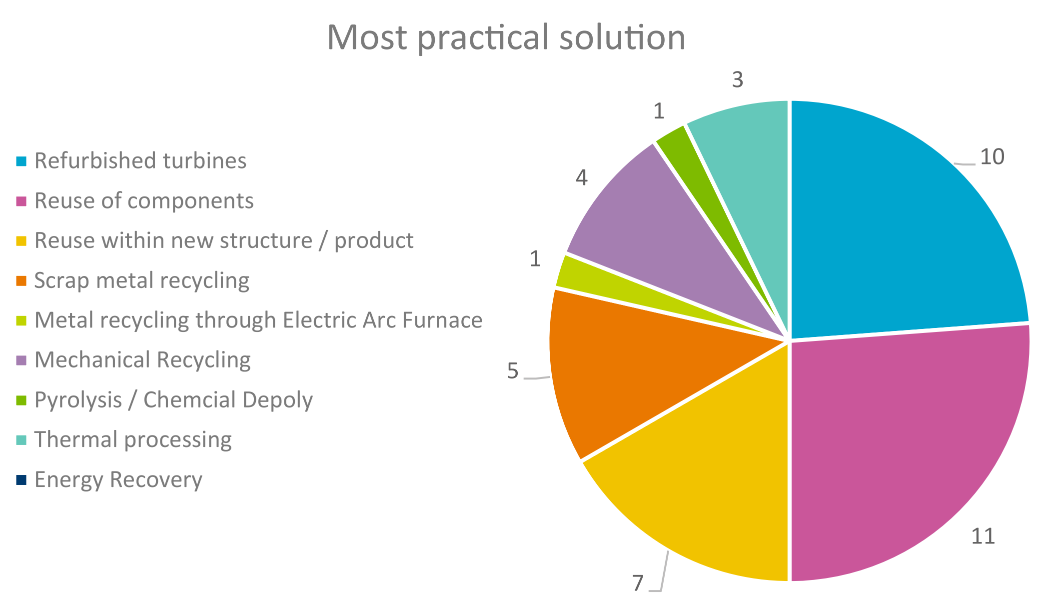
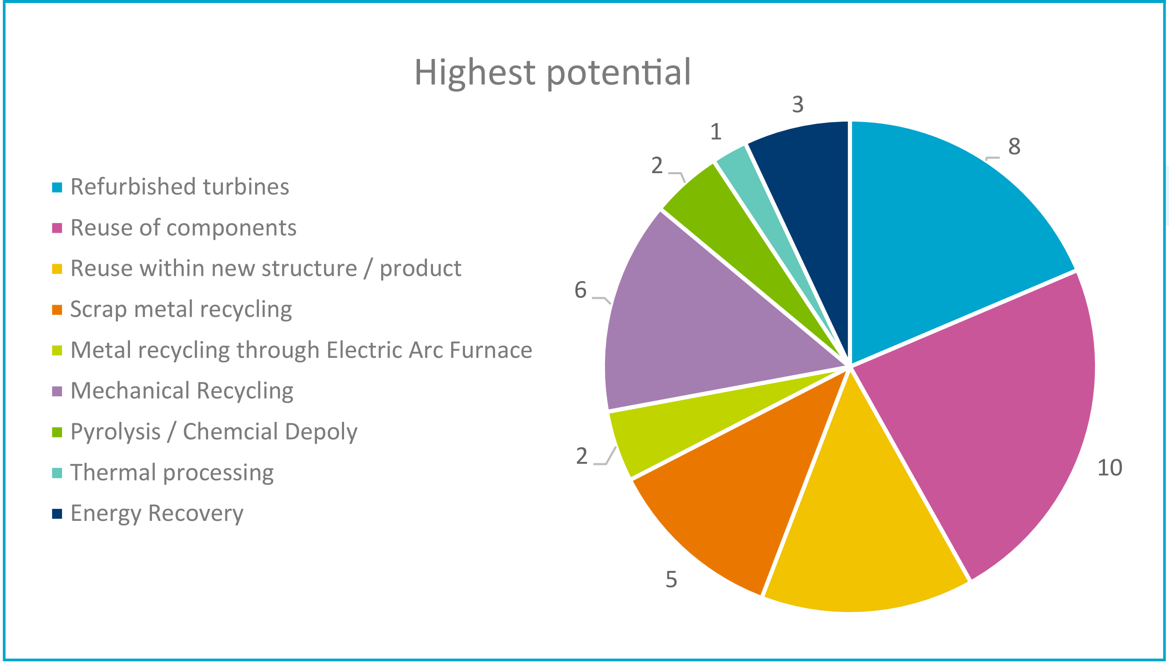


Figure 3.3: Highest potential from treatment solutions for onshore wind turbines based on survey responses



3.1.3.1 Full turbines

The MCA output for full turbines is demonstrated in Figure 3.1. The output concludes that the optimal treatment for full turbines is life extension, followed by refurbishment for use at a different location. This demonstrates a strong industry preference for life extension, as reflected in the interview and survey responses.

While GVA calculations used within the MCA favoured refurbishment over life extension, the uncertainty over Scottish value retention and lack of demand for refurbished turbines in Scotland was ultimately the distinguishing factor between the two treatment options.

3.1.3.2 Components

The MCA output for components is illustrated in Figure 3.1. For all components other than the wind turbine blades, the output concludes that the optimal treatment for components is refurbishment of components for use in a different location, followed by life extension and the various recycling treatment options. Landfill and thermal processing were assessed the worst treatment options. 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 there is 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 noted that because it is assumed that refurbished components are often processed abroad in original equipment manufacturer (OEM) takeback schemes, that recycled materials are processed or sold outside of Scotland. This impacts the MCA score for refurbished components as value retention in Scotland is lower than life extension; therefore, efforts to address value retention through refurbishment facilities and material processing facilities in Scotland should be a priority.

Finally, the blades are the exception for components, as they have more value through life extension than refurbishment. This is due to a lack of demand or potential Scottish value retention for refurbished blades. Refurbished blades are seen as high risk throughout the industry, as the cost of failure outweighs potential savings. As yet, no accepted recertification of refurbished blades exists, and significant effort would be required to create industry confidence in any procedure attempting to do so.

3.1.3.3 Materials

The MCA output for materials is set out in Table 3.4. For fibreglass, a preference can be seen for mechanical recycling; while the margins between the different treatment options are small, the survey results showed a clear preference for this option, possibly supported by Scottish involvement in the LifeBrio project (2017). Despite expectations that demand exists for the material outputs from recycling options, the barriers that impact fibreglass treatment options are simply that infrastructure does not currently exist to process fibreglass in Scotland. This removes the potential for value retention, value of materials and scalability. Mechanical recycling is seen as simpler and less intensive process in regard to necessary infrastructure, as well as being recognised as a viable solution in Scotland. However, a potential avenue for exploration could be the various pyrolysis plants planned for Scotland through Recycling Technologies, Perthshire (Recycling Technologies, 2021). While not currently set up for the processing of fibreglass, it does offer some potential for harnessing existing expertise, technologies, and infrastructure from within the UK.

Additionally, two active demonstration projects 'Circular Economy in the Wind Sector' (Offshore Renewable Energy Catapult, 2021) and the National Composites Centre's SusWIND project (NCCUK, 2021) are actively engaged in end-of-life options for turbine blades, offering potential to resolve some of the existing uncertainties and supporting a potential roadmap for developing solutions.

For steel, iron and copper, the established metal recycling processes rank highest. However, the fact that approximately 60% of recycled metal (BMRA, 2021) is currently exported abroad results in lower scoring through value retention.

3.1.3.4 Life extension in light of repowering and subsidies

Current onshore industry practices are focused on life extension of the turbines, but it is important to identify this as a finite activity that relies on the decommissioning and refurbishing of existing components. Additionally, life extension cannot continue indefinitely and a turbine will require alternative treatments as maintenance becomes more onerous or financially restrictive.

While it may seem counter-intuitive, decommissioning and repowering can have a positive impact upon circular economy processes, allowing life extension to occur for other turbines. Following the removal of subsidies in 2015, there has been a limited business case for owner/operators to repower. As a result, the Scottish onshore sector has been treating life extension as the norm. This may change following the 2020 announcement that onshore wind is eligible to compete in Contracts for Difference auctions.

While the MCA indicates life extension as the optimal method to apply for circular economy, it relies on the replenishment of components. However, as Scottish turbine models are often older, there is a concern that OEMs will no longer supply parts for these turbines, and they will become increasingly scarce. This is a limiting factor of Scottish onshore turbine life extension; if the industry focuses solely this treatment option it may not be able to continue without intervention. Repowering could be an important factor in maintaining the parts inventory necessary for circular reuse of components for life extension.

4. Task 3: Value of Options

4.1.1 Methodology for cost assessment

Decommissioning of turbines has the potential to generate cost or income for the owner/operator based upon the treatment options used. A basic assessment for the cost or value generated through treatment options of decommissioned onshore wind turbines in Scotland has been developed using a baseline disposal route based on current practice. The assessment has applied assumptions on components and material composition described in the inventory in table 1 of Martinez et al. (2009) which was also used to model the decommissioning forecasts set out in Task 1 (Section 2).

Desk-based research identified price per tonne of materials through recycling to generate potential revenue, alongside costs of disposal per tonne applied to processes such as landfill or energy recovery. Information on prices and costs were identified via interviews, Ricardo (2017), WRAP (2019) and Letsrecycle.com (2021) and data taken from projects undertaken as part of Zero Waste Scotland Circular Economy Business Support.

Average material weight data and recycling/landfill ratios were extrapolated for each turbine category, based on the decommissioning forecast model set out in Task 1 (Section 2). Appendix 2 provides a breakdown of material weights and the treatment method applied in the baseline scenario.

For the baseline, the price per tonne and cost per tonne were applied to average material weight data and recycling/landfill ratios, creating a baseline value or cost per turbine.

This same calculation methodology was applied to the different treatment options, by adjusting the recycling/landfill ratios to fit the described scenario. For example, in the treatment option of all waste being sent to landfill, the landfill disposal cost was applied to all material weights. Further descriptions on the scenario assumptions can be found in Section 4.1.2. The outcome of the calculations can be found in Table 4.1.

Treatment of materials is not the sole cost associated with the decommissioning process, therefore, additional costs associated with on-site crane hire, transportation, employment costs, facilities and logistics planning of the turbines has been applied in Table 4.2 to provide a clearer understanding of the potential cost or revenue of turbine decommissioning treatment options for the owner /operator. The adjusted calculations in Table 4.2 provide owner operators with estimates for the full process of treatment, allowing for conclusions to be made regarding the business case for treatment routes.

4.1.2 Assumptions and Limitations

The following assumptions and limitations have been applied to the cost assessment.

- Uncertainties around life extension conditions exist, such as number of additional operational years and maintenance requirements. Therefore, no calculation can be made.
- Refurbishment of full turbine and reuse of components in a different turbine assumes USD 150,000 per MW = £107,885 per MW[3].
- Reuse in a new structure lacks basic information as limited established market exists in Scotland for comparison. Therefore, costs have not been attributed to this treatment option.
- The baseline uses the cost and value of material recycling and disposal treatment processes described in Appendix 2, based on the forecasting model set out in Task 1.
- Material recycling assumes the same treatment methods for all metal as the baseline and all non-metal materials are processed but incur costs for treatment in line with landfill costs.
- Energy recovery assumes all metal is recycled and all non-metal materials are processed for energy recovery. Energy is recovered from materials only and the operator does not generate electricity revenues through this process.
- Landfill assumes **all** materials are sent to landfill.
- For the purposes of decommissioning cost calculation which is given as £30,000 per MW. Therefore, Category S assumes 0.5MW capacity; A assumes 1MW capacity; B assumes 2MW capacity; C assumes 3MW capacity.

4.1.3 Cost assessment

Table 4.1 describes the cost generated or value created for owner/operator for the baseline and by employing the different treatment options discussed in Task 2.

Table 4.1: Cost (-) & Value (+) assessment of turbine treatment

		Treatment options					
Turbine Category	**Life extension**	**Refurbishment of full turbine**	**Reuse components**	**Reuse in a new structure**	**Baseline**	**Energy recovery**	**Landfill**
S	-	£53,943	£53,943	-	£5,476	£5,908	-£3,870
A	-	£107,885	£107,885	-	£15,066	£32,616	-£21,377
B	-	£215,770	£215,770	-	£51,239	£51,438	-£33,713
C	-	£323,655	£323,655	-	£83,047	£54,938	-£36,007

The outcome of the cost assessment in Table 4.1 broadly aligns to the idea that the treatment options with greater resource efficiency offer the greater value. In regard to energy recovery, it should be noted that the metal content would be recycled as scrap, providing revenue that exceeds the gate fee for energy recovery from fibreglass, resin and silica.

Figure 4.1 shows a breakdown of the revenue generated or cost incurred of disposing of a 2MW turbine using current methods. It shows that much of the material value is generated through the recycling of steel which is the largest material flow by volume resulting from onshore wind decommissioning in Scotland to 2050.

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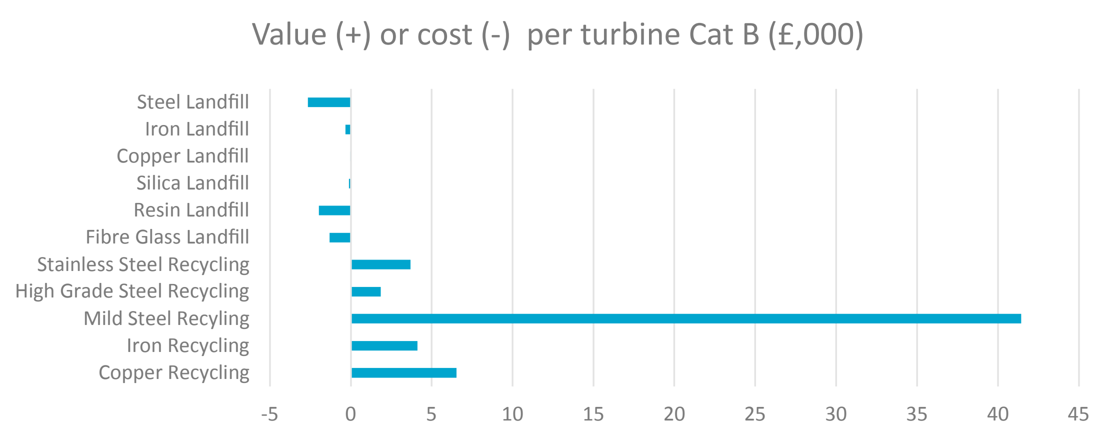
[3] Taken from projects undertaken as part of Zero Waste Scotland Circular Economy Business Support and verified during interviews.

Figure 4.1: Value (+) or cost (-) per 2MW turbine



While Table 4.1 provides a description of the material costs and value, treatment of materials does not represent the full picture as decommissioning will incur costs associated with on-site disassembly and transportation for treatment. It is currently estimated that a cost of £30,000 per MW for an onshore wind turbine will be required to account for crane hire, transportation, employment costs, facilities and logistics planning (Renewables UK, 2012). Table 4.2 accounts for the cost of disposal and decommissioning.

Table 4.2 Cost (-) & Value (+) assessment turbine treatment inclusive of decommissioning cost[4]

		Treatment options					
Turbine Category	**Life extension**	**Refurbishment of full turbine**	**Reuse components**	**Reuse in a new structure**	**Baseline**	**Energy recovery**	**Landfill**
S	-	£38,943	£38,943	-	-£9,524	-£9,449	-£18,638
A	-	£77,885	£77,885	-	-£14,934	-£11,314	-£42,247
B	-	£155,770	£155,770	-	-£8,761	-£8,062	-£94,040
C	-	£233,655	£233,655	-	-£6,953	-£5,821	-£145,171

The cost assessment indicates that refurbishment and reuse treatment options (Table 4.2) will generate significantly more revenue for the owner/operator for all four turbine categories, than traditional recycling or disposal.

While treatment of materials through recycling and energy recovery can generate revenue, this revenue is offset by the cost of decommissioning for all turbines, resulting in a cost per turbine to the owner/operator. Therefore, from a financial perspective, the treatment options that employ greater resource efficiency offer the best return.

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[4] Decommissioning costs £30,000/MW, Renewables UK, Onshore Wind Direct & Wider Economic Impacts (2012)) and verified during interviews.

4.1.4 CAPEX and OPEX of a new turbine

The average CAPEX cost of building new wind turbines (2016-19), weighted by capacity, is £1.55 million per MW in 2018 prices (Hughes, 2020).

The OPEX of an onshore wind turbine is expected to increase by 2.8% per year. A newly installed 2MW turbine had an expected annual OPEX cost of £142,400 in 2019; it would be anticipated to increase to £210,000 within 15 years (Hughes, 2020).

CAPEX and OPEX costs indicate the significant financial savings that can be made by owner/operators through Life Extension and efficient refurbishment or reuse as an alternative to installation of new turbines.

4.1.5 Methodology for Gross Value Added

Gross Value Added (GVA) calculations have been created for the treatment options outlined in Task 2 (Section 3).

The methodology employed identified the number of full-time employees[5] (FTE) by profession required for decommissioning a 2MW turbine. Data was utilised from 'Renewable Energy Benefits: Leveraging Local Capacity for Onshore Wind' (IRENA, 2017) to extrapolate the human resource required during decommissioning and treatment, separately.

Once the FTE were identified for decommissioning and for each treatment activity, a GVA per head ratio was applied to the data. GVA per head ratios were taken from the Scottish Annual Business Statistics 2018 (Scottish Government, 2020) to create a decommissioning baseline (excluding the treatment activity). Then additional GVA ratios were applied to FTE resource requirements for each treatment option, utilising GVA per head ratios. Appendix 3 describes the key assumptions applied for the GVA per ratios.

4.1.6 Gross Value Added results

Table 4.3 describes the GVA calculations for a 2MW turbine, broken down by decommissioning and treatment for the treatment options described in Task 2 (Section 3).

The GVA calculations described in Table 4.3 provide a high-level insight into value to the Scottish economy through the application of different treatment options. The assessment identifies value through decommissioning and treatment, indicating that significant value per turbine can be generated through decommissioning and treatment alone.

Specifically, the circular economy-based solutions of refurbishment, reuse of components and reuse in a new structure generate the highest GVA due to the involvement of highly skilled professions and supply chains. Therefore, when scaled across Scotland's entire onshore wind industry, there is potential for significant benefit from circular economy-based solutions when compared with landfill and energy recovery.

These GVA calculations only account for some of the potential value generated for the Scottish economy as it only describes value through decommissioning and treatment and does not capture expected value generated by retaining value for these assets in the Scottish economy through further construction, operation, maintenance and/or reuse of materials. Therefore, this assessment has identified that higher GVA can be generated through circular economy base solutions such as life extension, refurbishment, reuse, and material recycling. Recommendations to investigate these benefits further are identified in Section 4.1.7.

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[4] Decommissioning costs £30,000/MW, Renewables UK, Onshore Wind Direct & Wider Economic Impacts (2012)) and verified during interviews.

Table 4.3: GVA for treatment options

	GVA £ per 2MW turbine per year (Cat B)		
Treatment option	**Decommissioning (without treatment)**	**Treatment specific**	**Total**
Life extension	-	-	£0
Refurbishment	£58,919	£14,073	£72,992
Reuse of components	£58,919	£14,073	£72,992
Reuse in a new structure	£58,919	£14,073	£72,992
Material recycling	£58,919	£10,618	£69,537
Energy recovery	£58,919	£7,612	£66,531
Landfill	£58,919	£7,612	£66,531

For life extension and refurbishment to occur, there are core dependencies on other circular economy treatment processes, such as the refurbishment of components. Life extension and refurbishment offer GVA value not discussed in this study/report, but in order for that to be realised circular economy-based solutions need to be harnessed, which in turn would generate additional GVA to the Scottish economy. Furthermore, additional benefits of scale could be generated through alignment to adjacent industries, such as offshore wind or even the fibreglass industry.

4.1.7 Next Steps

The GVA figures presented in Table 4.3 cover only decommissioning and disposal. For example, the life extension treatment option creates no GVA through decommissioning or disposal but evidently will create GVA due to the GVA associated with operation and maintenance over an extended period. Further exploration is required to account for additional GVA from recommissioning, continued operation, additional maintenance, and indirect employment for most of the treatment options. Table 4.4 identifies scope for further review of GVA and the factors where further value may be realised associated with the treatment options.

Table 4.4: Potential GVA from extended lifecycles of materials

	Applicable GVA factors					
Turbine Category	**Decommissioning (without disposal)**	**Treatment of materials**	**Recommissioning**	**Operation**	**Maintenance**	**Indirect employment**
Life extension	–	–	–	✓	✓	✓
Refurbishment	✓	✓	✓	✓	✓	✓
Reuse of components	✓	✓	–	✓	✓	✓
Reuse in a new structure	✓	✓	–	?	?	✓
Material recycling	✓	✓	–	?	?	✓
Energy recovery	✓	✓	–	–	–	✓
Landfill	✓	✓	–	–	–	✓

5. Task 4: Carbon Impact of Options

5.1.1 Methodology

To estimate the emissions from wind turbine decommissioning between 2021 and 2050, a carbon model was developed using Microsoft Excel. The inputs included data drawn from the following sources:

1. The wind turbine decommissioning forecasts set out in Section 2 (Task 1).
2. Emission Factors for relevant materials provided by the Inventory of Carbon Emissions (ICE) Database V3.0 (2019).
3. Emission Factors for transport provided by BEIS (2020).

The model included the weight of materials used in the manufacturing of a typical 223 tonne 2MW wind turbine. The proportion of the total turbine weight that each of these materials accounted for was applied to each of the three categories of wind turbines being considered to give the weight of each material per turbine. Using the Emission Factors within the ICE Database, a basic carbon footprint was calculated to determine the embodied carbon emissions associated with the manufacture of each of the three turbine categories using virgin materials. The same calculation was then applied to determine the embodied carbon content of the three turbine categories using materials with recycled content. This allowed for a comparison of emissions between virgin and recycled content during the manufacturing process. This captures the "Cradle to Gate" emissions which include those from sourcing of raw materials and the manufacture of the turbine.

To calculate transport emissions, the RUK database was used to count the number of turbines in each of Scotland's 32 Local Authorities (LA). Three locations have been proposed as assumed turbine decommissioning hubs: Peterhead, Dunbar and Methil to represent a location in Central, Southern and Northern Scotland respectively where there are clusters of wind farms. While these locations are representative only, ports would serve the offshore wind sector so offer co-location opportunities and, following research for Task 5 (Process Of Storing And Separating Materials), presented in Section 5, ports are well placed to deal with decommissioned components.

The centre-point of each LA was determined and the distance from this point to each of the three proposed decommissioning hubs was measured. Due to the complexities involved in transporting large turbine components, the 'freighting goods' tonnes.kilometre emission factor of 0.07773 kgCO_2e from BEIS was applied to represent articulated lorries greater than 33 tonnes. This is an equivalent measure of emissions from one tonne of transported goods over one kilometre. Using the number of Category A-C turbines to be decommissioned in the High and Low forecasts in each LA, the total weight of turbine components for each category was calculated. The distance from the centre point of each LA was multiplied by the turbine component weight and multiplied by the 0.07773 kgCO_2e emission factor to estimate the emissions for transporting the turbines within each LA to each of the three decommissioning hubs. The optimal location for the hub could then be determined, considering the regions with the greatest concentration of turbines and the fewest driven kilometres.

5.1.2 Limitations

Establishing a baseline for current waste management of turbines proved challenging. From the research undertaken and given the infancy of decommissioning in Scotland, there is very little evidence to substantiate whether turbines are being managed/disposed in UK, managed abroad and if so, where. Therefore, to extrapolate this baseline for a carbon model would not present a credible estimate to inform decision making in the industry.

There are also limitations when applying the BEIS waste disposal factors as the emissions associated with recycling and energy recovery are attributed to the organisation which uses the recycled material, or which uses the waste to generate energy. The BEIS factors don't consider the process emissions during waste treatment and are therefore not useful for comparing recycling versus landfill emissions.

5.1.3 Carbon Model

The emissions calculated for the scenarios are discussed in this section and presented in Figures 5.1 to 5-4.

The emissions from the manufacturing of onshore wind turbines using recycled content materials are approximately 35% lower than manufacturing using virgin materials. Steel is the most prevalent material used in turbine manufacturing, accounting for 75% of manufacturing emissions when using virgin steel and 61% when recycled content steel is used. Recycled content steel has 46% lower emissions than virgin content and this is where the majority of the 35% saving originates from. However, some recycled content materials have higher emissions, including copper which has 29% higher emissions due to the energy intensity of re-processing.

Figure 5.1: Emissions share for turbine manufacture using virgin materials

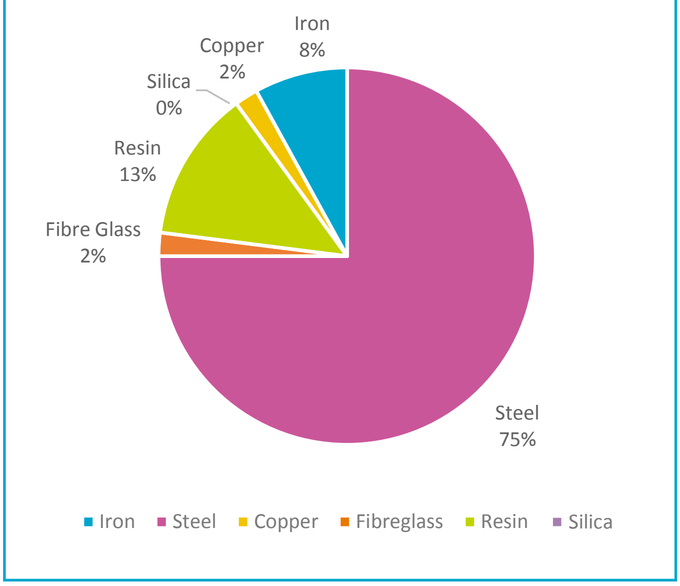


Figure 5.2: Emissions share for turbine manufacture using recycled materials

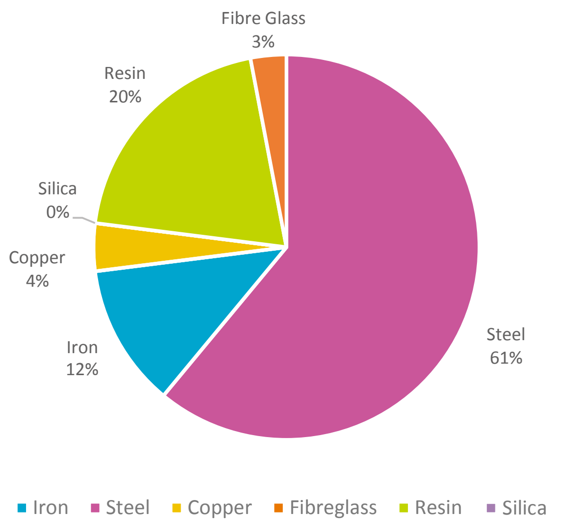
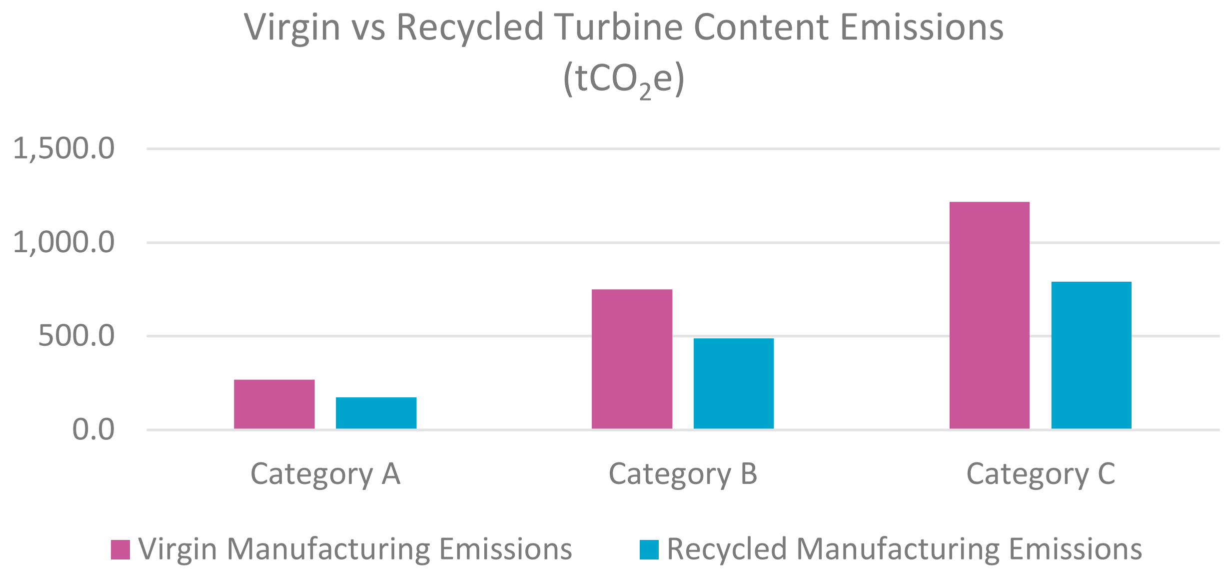
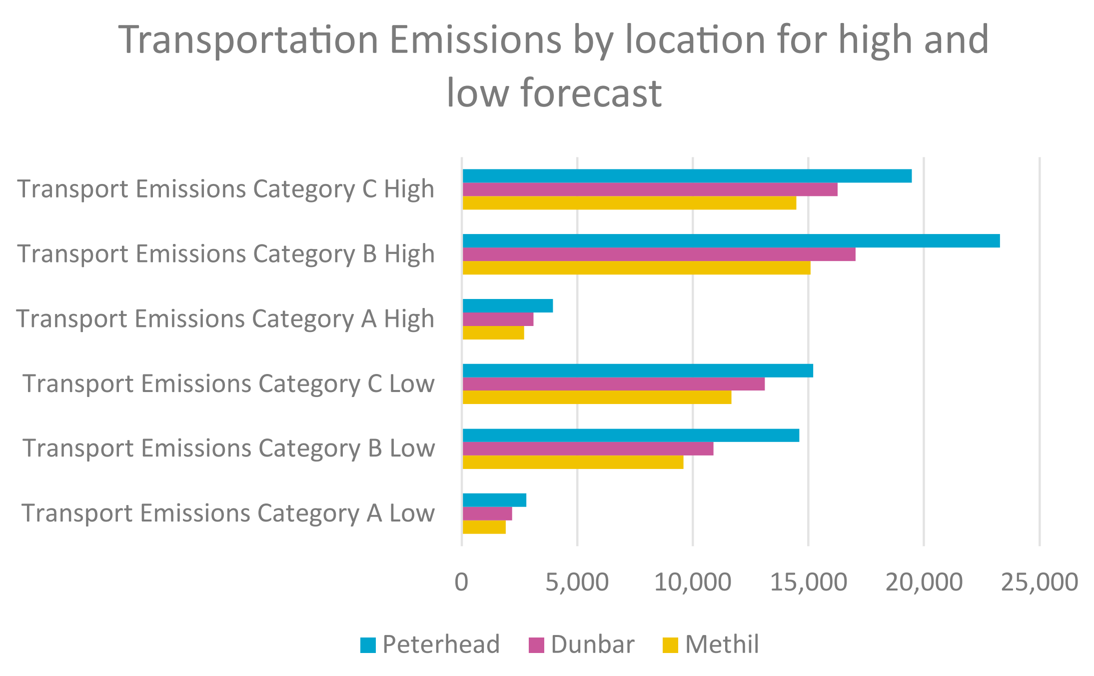


Figure 5.3: Virgin vs Recycled Content Turbine Manufacturing Emissions (tCO_2e)



The estimated transportation emissions were then calculated using the method outlined in Section 5.1.1. As shown on Figure 5.4, Methil was determined to have the lowest transport emissions from the three representative locations for all turbine categories under both the High and Low decommissioning forecasts. This equates to the fewest driven kilometres required to transport the turbines across the country to Methil.

Figure 5.4: Transportation Emissions by location for high and low forecast (tCO_2e)



5.1.4 Next Steps

The figures presented here primarily focus on the manufacturing and transport emissions due to the limitations of the BEIS waste factors as set out in Section 5.1.2. The assessment presented above considers 'cradle to gate' emissions. Further work on developing an accurate methodology to consider the process emissions associated with the treatment options would be beneficial for this sector, as well as the waste management sector as a whole.

In 2020, the UK government announced a ban on the sale of petrol and diesel cars and vans from 2030, but this did not include diesel Heavy Goods Vehicles. To contribute towards the Scottish Government's legislated target of net-zero emissions by 2045, the haulage industry will need to adopt zero-emission vehicles. This will likely be driven by vehicle manufacturers through research and development to bring cost-competitive alternatively fuelled vehicles to market. The carbon modelling should be refined as the Scottish haulage industry adopts zero-emission vehicles.

6. Task 5: Process of Storing and Separating Materials

A review was undertaken to better understand the space and manoeuvring constraints that exist during decommissioning. Table 6.1 summarises the output from a literature review, market survey, market interviews, identifying key storage and separation considerations. These include:

- onsite dismantling and disassembly;
- transportation and manoeuvring; and
- dismantling and storage requirements.

Interviews were undertaken as part of Task 7 (Section 8) to inform and validate the initial requirements for decommissioning. Specifically, interview responses on this topic from Jacobs Wind Farm Operations Manager, Renewable Parts and Scottish Power Renewables and key literature review included but wasn't limited to DIN SPEC 4866:2020-08, Wind Europe (2020), Scottish Natural Heritage (NatureScot, 2013), RUK (2012) and ReGlobal (2020) where a valuable source of information.

The survey respondents identified that their biggest challenge in decommissioning occurred during transportation of turbine components and the storage and processing, as displayed in Figure 6.1

Figure 6.1: The Biggest Logistical Challenge For Decommissioning

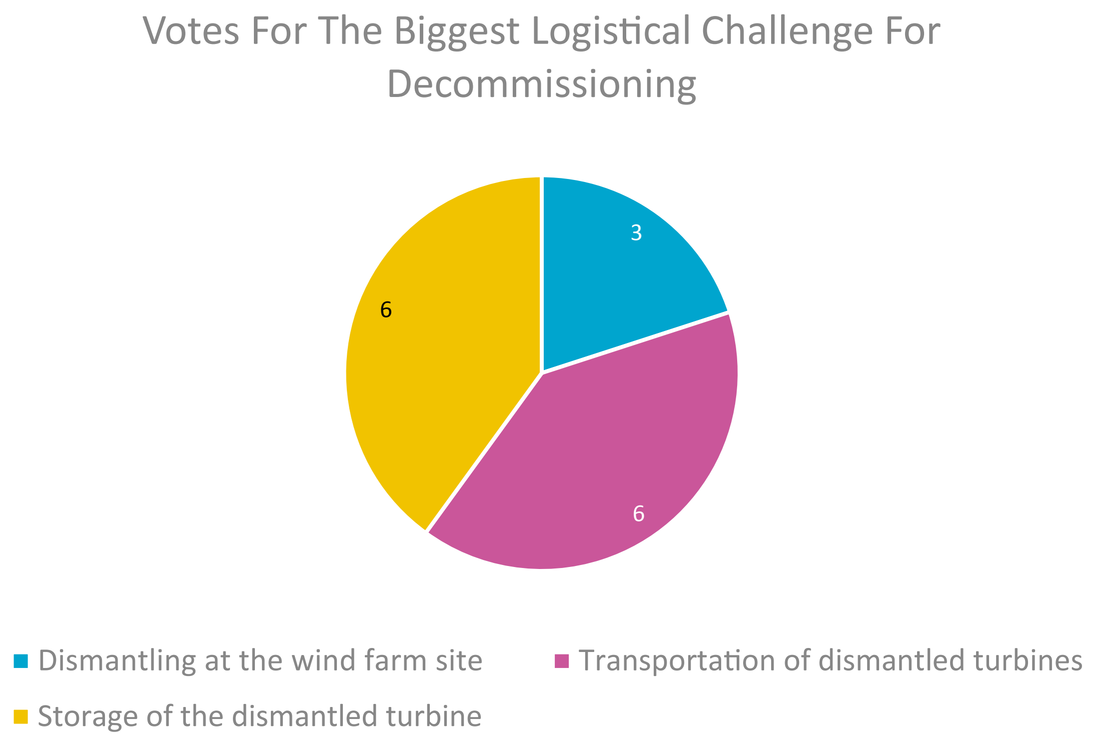


Table 6.1: Onsite dismantling and disassembly

Process	Key Considerations
Personnel	• Personnel needs are comparable to installation. • Quantity per turbine: 2-3 operating inside the turbine; 2 crane crew; and 1 lift supervisor.
Risks / barriers	• Onshore turbine construction has been limited in the recent past with the removal of subsidy between 2015-2020. As construction and decommissioning require similar skills and equipment, the lower rates of construction mean that skilled personnel are limited. As construction and decommissioning of turbines increases, there could be a skills shortage. • Availability of equipment such as cranes could be limited due to recent construction trends, as stated above. • Most wind turbine manuals contain little content on decommissioning and information is inconsistent between turbine models. • Potential deterioration of original crane hardstanding from construction. • Hazardous / contaminated materials may be present and must be safely disposed of during decommissioning. • Lubricants and other hazardous substances may be present from within components such as gearboxes.
Preparation for dismantling	• Decommissioning bond conditions need to be identified from the outset. • The planning conditions in original consent must be addressed if they have been specified; however, current practice shows limited detail of plans is required. • The operator bears the overall responsibility for the dismantling. • The local authority is expected to have a responsibility as a supervisor. • Documentation for the wind turbine is required inclusive of disassembly instructions, design drawings, foundation drawings, statics, type testing, contaminant assessments, soil assessments, building permit and history of the wind turbine. • Prior to dismantling, preparation of a Site Waste Management Plan, a Material Management Plan and a Site Restoration Plan must be completed by the owner/operator. • The EU Waste Framework Directive (2008/98/EC) defines basic concepts related to waste management. • HSE (Health Safety and Environment) Risk Assessment and Method.
Equipment and process	• Dismantling equipment is comparable to that required in construction. • Disassembly expected to take approx. 2 to 3 days. • 2 x cranes required per turbine. • Power is required to manoeuvre the turbine components at different stages. • Offices, recreation rooms and sanitary facilities, crane lifters, riggers, welfare facilities need to be established at site. • Hardstanding restoration and reinstatement.

Table 6.2: Transportation and manoeuvring

Process	Key Considerations
Risks / barriers	• Road infrastructure may have changed since commissioning, creating new hazards and access barriers. • New development around the site (e.g., recreational paths) can prevent movement. • Lower rates of recent onshore construction for turbines could mean that the availability of turbine transportation vehicles is limited.
Preparation for transportation	• Only trained, certified and competent personnel may be deployed during loading/unloading/stacking and transportation. • Specialist companies exist to manage transport of turbines, providing vehicles and personnel. • Transport and Traffic Management Plan requirements from local authorities and to coordinate supply chain and other stakeholders. • The Transport and Traffic Management Plan created prior to the commissioning as a requirement from the consenting authority describes how to get components to site and this is a useful reference point. • Special loads application for blades and the tower from the highways agency will be required. • Highways agency permitting for transport of extreme loads will be required. • Based on component and scales, police support is anticipated.
Equipment and process	• Custom packaging frames need to be created ready for storage and transportation. • Support convoy vehicles (2 per heavy load vehicle). • 1 x Heavy load vehicle per nacelle. • 3 x Heavy load vehicle per tower. • 1 x Heavy load vehicle for 3 blades, providing transport frame in place. • 3 x Heavy load vehicle for 3 blades if no specialist transport frame in place. • Move street furniture if required – coordinate with highways agency to authorise (and police). • Receipt site needs to have clear entry with no pinch points.

Table 6.3: Dismantling and storage requirements

Process	Key Considerations
Risks / barriers	• Competition for space with offshore industry therefore needs planning if to be integrated. • Limited access to mechanical shredders.
Locations	• Given current infrastructure and supply chain, ports are viewed as the optimal location for further dismantling. ◦ Most turbines arrive via ports. ◦ Most OEM based maintenance and disposal requires shipping. For example, Vestas take-back scheme requires shipping to The Netherlands. • Given the location of existing wind farms shown in Figure 2.5 the representative port locations at Methil, Peterhead, and Dunbar (and Nigg) would accommodate the distribution of components. ◦ All have experience of handling wind turbines. • Ports have extensive storage areas, warehousing, and deep-water berths. • Some ports contain existing infrastructure to accommodate offshore wind. • In addition, Port of Dundee and Port of Leith were identified as key assets in the National Renewables Infrastructure Plan (NRIP). • Port of Dundee is part of the Scottish Government's Low Carbon Renewables East Enterprise Area. • Ports often possess large lay down areas and heavy lift capacity.
Equipment and space	• Port of Nigg, as a sample location based on its involvement in onshore and offshore wind industry: ◦ 700,000m2 open manoeuvring space; ◦ 36,000m2 indoor storage; ◦ 232,000m2 outdoor storage; and ◦ 2 x 55 tonne pipe gantry cranes. • Peterhead: ◦ 16,000m2 open manoeuvring space plus 32,000m2 reclaimed land available for processing and storage; and ◦ 5,000t crane lifting capacity. • Brownfield sites of comparable scale could be adapted to manage dismantling and storage. However, road infrastructure and the availability to shipping network creates more favourable conditions for locations near major ports.

7. Task 6: Opportunities in Moving to A Circular Approach to Decommissioning Materials

Table 7.1 is presented to inform a future guide for onshore wind decommissioning for a circular economy in Scotland. It identifies key opportunities such as changes to design, legislation, public and private investment, commitments from owner/operators, skills & training, and potential locations for reprocessing. Key considerations and risks have been identified alongside recommended actions for Zero Waste Scotland, the onshore wind industry and the Scottish Government.

When surveyed, industry respondents identified that the greatest opportunities to support a circular economy within the industry was through focusing on future reprocessing infrastructure and storage locations. This coincided with the future reprocessing infrastructure also being identified as the greatest barrier. Essentially, the infrastructure requires focused attention ahead of changes to regulations and asset design and management level. As identified by one interview correspondent, legislating circular economy-based solutions will only create future barriers that cannot be overcome if the required infrastructure is not in place.

Furthermore, industry respondents identified that the Scottish Government and the onshore wind industry itself are best placed to resolve these barriers, due to the complexity and potential investment required.

To improve market conditions for circular economy-based solutions in decommissioning, the market must acknowledge the baseline conditions, such as:

- There is a lack of dedicated infrastructure to dismantle, transport and process wind turbines.
- There is a limited established market in Scotland for dealing with full turbines and materials.
- The refurbishment market is dominated by OEMs based abroad.
- There is uncertainty over the volume of materials and components.

- There is a complex parts inventory and non-OEM supply chain is not equipped with the information to navigate.
- There is limited legislative guidance.
- There is a potential absence of skills and expected competition resulting from offshore wind decommissioning.
- There is limited information on how OEMs are incorporating design developments to increase circular economy opportunities in decommissioning.

However, based on the work undertaken a series of enablers have been identified to either better inform or address the existing barriers:

- Forecasting undertaken in Task 1 (reported in Section 2 of this report) shows that sufficient volumes of turbines, components and materials will occur through decommissioning to support the need and business case for direct market support for onshore wind decommissioning.
- Ports across Scotland are well placed to respond to infrastructure needs required to develop the market for circular onshore wind decommissioning.
- The emergence of new material processing technology has strong links to Scotland.
- Brexit adjusting trading relationship for non-UK based OEMs.
- Past operator and academic partnerships offer roadmap to skills growth.
- There is operator interest in setting up an onshore wind energy council on decommissioning.
- With respect to planning policy, the National Planning Framework 4 Position Statement (Scottish Government, 2020) advises that “Planning can facilitate low carbon methods of construction, which create a whole building approach to emissions including construction and decommissioning”, and it is expected that this could be expressed through direct policy support in NPF4 for developments that make use of low carbon materials and the retention of existing materials. This should be advocated and followed through at local authority level through the adoption of proactive development plan policies, supplementary guidance and the planning applications process, with the aim of supporting and facilitating proposals for recommissioning onshore wind turbines where these are consistent with wider spatial aims and policies in NPF4 and the local development plan.

Table 7.1: Opportunities, risks and actions for circular economy-based decommissioning

			Recommended actions		
Opportunities	**Key considerations**	**Risks**	**Zero Waste Scotland**	**Industry**	**Scottish Government & Agencies**
Amendments to prepare existing assets for decommissioning	• Availability of guidelines for disassembly. • Large number of OEMs and variance on models in use in Scotland. • OEMs and tier 1, 2 and 3 supply chain in Scotland. • OEM takeback schemes exchange turbine components requiring offsite repair with new or refurbished parts from the supplier. These are based outside of Scotland influencing the material flow and value retention. • OEM service and maintenance contracts influence development of supply chain in Scotland. • Limited established Scottish supply chain with insufficient scale to address the market. • Scottish market trend for life extension over 10 additional years.	• Complex parts inventory creates barrier for supply chain to identify solutions. • Uncertainty and lack of available data relating to volume of materials and components, preventing market opportunities to be identified.Recycled material export limits Scottish value retention. • Lack of demand for refurbished blades will create waste through repowering and decommissioning. • Increased supply of components from decommissioning will disrupt process and business case for supply chain. • Complex planning for the movement of refurbished components. • Many of Scotland's onshore turbines are older models, meaning parts for life extension will become scarce over time. • Older Scottish onshore turbines will have a limited market for reusing parts. • Operators pay premium for OEM maintenance and warranty to reduce risk. This restricts access to market for local business.	• Collaborate with Scottish Renewables to coordinate industry partners to create a step-by-step framework for decommissioning in Scotland. • Collaborate with Scottish Renewables to coordinate owner/operators to articulate their decommissioning needs, highlighting the potential for design changes. • Explore standards for blades certification / warranty scheme to encourage life extension of blades beyond 25 years. • Commission study into novel use of turbine components in Scotland, expanding on existing research and academic partnerships. • Align to existing cross industry studies from Catapult and NCC into fibreglass disposal treatment and volumes.	• Review opportunities for local market to focus on life extension / refurbishment of old turbines where operators are more sensitive to cost. • Review complexity of OEM part numbers and encourage transparency to improve ability to replace or recirculate components. • Validate decommissioning forecast model and output, providing further input on turbine model weight and material composition and anticipated decommissioning and repowering • Review Scottish opportunities for resale of decommissioning turbines and components • Align to existing cross industry studies from Catapult and NCC into fibreglass disposal treatment and volumes.	• Expand requirements in planning procedures to include more detail on end-of-life processes. • Review financial support for Scottish tier 2 & 3 supply chain. • Support for a Scottish reuse, repair and brokerage platform. • Assess feasibility for a decommissioning accelerator programme or decommissioning site.

Table 7.1: Opportunities, risks and actions for circular economy-based decommissioning

			Recommended actions		
Opportunities	**Key considerations**	**Risks**	**Zero Waste Scotland**	**Industry**	**Scottish Government & Agencies**
Amendments to the design of future assets for decommissioning	• Availability of guidelines for disassembly. • OEMs and tier 1, 2 and 3 supply chain in Scotland. • As assets have expected lifespans in excess of 25 years, any benefit through design amendments for future assets will not be realised until beyond the limits of this study. • OEM takeback schemes exchange turbine components requiring offsite repair with new or refurbished parts from the supplier. These are based outside of Scotland influencing the material flow and value retention. • OEM service and maintenance contracts influence development of supply chain in Scotland. • Limited established Scottish supply chain with insufficient scale to address the market.	• Industry not focused on design for decommissioning. • Complex parts inventory creates barrier for supply chain to identify solutions. • Uncertainty and lack of available data relating to volume of materials and components, preventing market opportunities to be identified. • Material recycling not economical for certain materials like fibreglass. • Recycled material export limits Scottish value retention. • Lack of demand for refurbished blades will create waste through repowering and decommissioning. • Complex planning for the movement of refurbished components. • Operators pay premium for OEM maintenance and warranty to reduce risk. This restricts access to market for local business.	• Collaborate with Scottish Renewables to coordinate owner/operators to articulate their decommissioning needs, highlighting the potential for design changes. • Explore standards for blades certification / warranty scheme to encourage life extension of blades beyond 25 years. • Commission study into novel use of turbine components in Scotland, expanding on existing research and academic partnerships. • Cross industry study into fibreglass disposal volumes.	• Increased dialogue with industry/owner operators focused on decommissioning process to facilitate design changes. • Review complexity of OEM part numbers and encourage transparency to improve ability to replace or recirculate components. • Modular design to allow for reuse of components and upgrades leading to life extension. Such design modifications can create greater efficiencies in the decommissioning process • Align to existing cross industry studies from Catapult and NCC into fibreglass disposal treatment and volumes. • Work with Academia to improve material selection based on disassembly; e.g., thermoset resins can be replaced with thermoplastics.	• Expand requirements in planning procedures to include more detail on end-of-life processes. • Introduce material passports for components. • Review financial support for Scottish tier 2 & 3 supply chain. • Commission Catapult Innovation and Research Centre to expand beyond offshore wind.

Table 7.1: Opportunities, risks and actions for circular economy-based decommissioning

			Recommended actions		
Opportunities	**Key considerations**	**Risks**	**Zero Waste Scotland**	**Industry**	**Scottish Government & Agencies**
				• Work with Academia to improve material selection based on scarcity; e.g., balsa wood alternatives may be necessary for blades. • Leased ownership models could be employed. This would involve operators leasing turbines from OEMs, and all materials returning to OEM responsibility at the end of lease term. OEMs are well placed to apply circular processes.	
Change in legislation, regulations, and planning	• End of life waste criteria/considerations for composite blade materials. • Planning guidance and regulation for decommissioning, directing owner/operators on decommissioning treatment. • The French Govt. set regulated targets on the percentage recycling for onshore wind turbines. Owners will be obliged to recycle at least 95%	• There is limited legislative guidance on decommissioning. • Complex planning regulations may discourage operators from reusing full turbines in Scotland. This is a significant barrier for smaller operators/landowners. • Repowering requires new planning consent, which encourages life extension. However, life extension of older models requires parts, often refurbished	• Support the Scottish Government to explore the formation of an onshore wind energy council to identify key legislative conditions and requirements for decommissioning. • Facilitate engagement between industry and SEPA to support development of "End of waste status" processes.	• Introduce producer responsibility over components with high failure rates (IE: gearbox) • OEM, Owner/Operator working group for decommissioning legislation. • Formulate industry-wide approach towards 'Right to Repair' legislation. • Proactively engage with SEPA to achieve "End of waste status" for turbine materials	• Create an onshore wind energy council to identify key legislative conditions and requirements for decommissioning. • Through NPF4, adoption of proactive development plan policies, supplementary guidance and the planning application process, support and facilitate

Table 7.1: Opportunities, risks and actions for circular economy-based decommissioning

			Recommended actions		
Opportunities	**Key considerations**	**Risks**	**Zero Waste Scotland**	**Industry**	**Scottish Government & Agencies**
	of the total weight of the turbine including foundations, from the 01/01/2024, and 55% of the rotor blades, from the 01/01/2025 (Greensolver, 2020). • Include requirements in original planning consent. • No recognised onshore industry bodies, • Tip Height restrictions in planning. • Repowering planning consent. • Market incentive schemes.	parts through circular processes. Low repowering rates could restrict the supply chain and hinder life extension. • Any regulatory intervention must coincide with supply chain market development to create capacity to meet any material processing requirements. • Attaining the conditions for "End of waste status," thus allowing a waste to re-classified as a coproduct for use by a third party, can be costly. • The previous removal of subsidies for the onshore wind industry has adjusted owner/operator's business cases; it has been more economical to extend existing turbine operational life than repower. However as many of Scotland's turbines are older models the supply chain may struggle to match demand for older model parts.		that are currently considered waste but could be reused or repurposed.	proposals for recommissioning onshore wind turbines where the application can demonstrate low carbon use of materials or retention of existing materials and where these are consistent with wider spatial aims and policies in NPF4 and the local development plan. • Consider update to guidance on decommissioning plans to support retaining and re-using materials as an aim and outcome. • Review and simplify consent extensions to increase the reuse of parts from salvaged turbines. • Review subsidy of onshore wind to address disincentives impacting the market supply of

Table 7.1: Opportunities, risks and actions for circular economy-based decommissioning

			Recommended actions		
Opportunities	**Key considerations**	**Risks**	**Zero Waste Scotland**	**Industry**	**Scottish Government & Agencies**
					refurbished parts for life extension. • SEPA to work with industry requests for "End of waste status" for turbine materials with the aim of allowing a waste to reclassified as a coproduct for use by a third party. • Legislate for recycling targets from turbines. The French Government set specific requirements on turbine treatment to ensure value is retained from materials (Greensolver, 2020). • Fines and penalties for abandoning turbines and their components on green field sites. • Incentivisation for repowering to stimulate circular economy processing like reuse and refurbishment while also increasing generation capacity. • Support planning for smaller developments sites. This could assist the reuse of smaller reconditioned turbines.

Table 7.1: Opportunities, risks and actions for circular economy-based decommissioning

			Recommended actions		
Opportunities	**Key considerations**	**Risks**	**Zero Waste Scotland**	**Industry**	**Scottish Government & Agencies**
Public and private investment	• Investments to enable decommissioning infrastructure. • Investment in research for end of life uses. • Incentivise Scottish market for reprocessing materials. • The current market conditions, infrastructure and supply chain for refurbishing is limited and not mature. • Brexit adjusting trading relationship for non-UK based OEMs.	• Low rates of onshore commissioning in recent years means transferable skills and equipment may be limited as new turbines are commissioned and old turbines are decommissioned. • Limited market in Scotland for using and selling full turbines. • Difficult to regulate for circular economy as there is no market to respond at present. • Lack of new onshore wind construction in the UK is limiting the demand for refurbishment for second use (full turbine). • The lack of new sites means that many of the spare parts will eventually have little demand or demand becomes saturated in Scotland. • Grid connection availability heavily influences the timing of decisions and the business case. This creates uncertainty. • Uncertainty over volume of materials and components is preventing circular economy organisations from identifying market opportunities.	• Commission study into novel use of turbine components in Scotland, expanding on existing research and academic partnerships. • Commission study into innovative decommissioning technology in Scotland, prioritising mechanical recycling and potentially pyrolysis. • Support refurbishing SMEs to address late turbine lifecycle stages for opportunities to growth. As turbines are older, owner/operators are most sensitive to maintenance costs. As owner/operators consider OEM warranties on new parts less important, an opportunity arises for SME's to address this market. • Review of market conditions in light of Brexit.	• Perform a grid capacity review to identify requirements in relation to repowering growth. Repowering may be required to support other circular processes and increase capacity of site, but repowering could be limited by grid capacity. • Providing investment for new recoverable composites. • Identify investment opportunities or partnerships with Scottish tier 1 and 2 suppliers to develop local supply chains. • Investment in Scottish sites for refurbishment and maintenance to reduce movement of parts abroad. Potential contribution/ involvement in Scottish decommissioning hub.	• Identify or create the levers for investment – Green Investment Portfolio, National Investment Bank. • Encourage and incentivise internal Scottish market so decommissioned turbines are recommissioned in Scotland. • Incentivise market growth in novel recycling technology. • Incentivise market growth in novel use of turbine components. • Incentivise ports to respond to infrastructure needs through National Renewables Infrastructure Plan or Low Carbon Renewables Enterprise Areas. • Incentivise market for mechanical recycling. Align with Scottish Power to explore outcomes of LifeBrio project and opportunities to implement findings. • Administer a review on grid access requirements to provide timely access for owner/operators in commissioning, repowering, and recommissioning of refurbished turbines.

Table 7.1: Opportunities, risks and actions for circular economy-based decommissioning

			Recommended actions		
Opportunities	**Key considerations**	**Risks**	**Zero Waste Scotland**	**Industry**	**Scottish Government & Agencies**
Commitments from owner/operators	• OEM Environmental policies. • Operator environmental policies. • Maintenance scheduling commitments. • Lead time on EU parts. • Monitoring and measurement of components. • Absence of onshore wind energy council to for decommissioning to establish standard methods of practice.	• Customer demand for circular solutions / design for decommissioning from OEM is not mature. • Market for refurbishment is dominated by OEMs based abroad. • OEM long term agreements for maintenance restrict tier 2 & 3 suppliers. • Absence of agreed certification for refurbished parts results in OEM dominance. • Lack of business case for OEMs to operate in UK. • OEMs location reduces value retention in Scotland. • Perceived risk of refurbished blades. • Competition on parts/ turbines from EU. • Complexity of parts inventory causes delays for non-OEM refurbishment, allowing OEMs to provide parts at cheaper prices.	• Harness owner/ operator interest in creating an onshore wind energy council to organise conditions requirements for decommissioning. • Study to identify scale of market for SMEs; potential focus on opportunities for older turbine models where OEM's are more price sensitive in regard to maintenance.	• Review of schedule of environment commitments in practice to address inconsistency of policies and implementation. • Linking decommissioning to carbon reduction commitments. • Introduce lifetime extension certificates. • OEM partnerships with Scottish tier 2 & 3 supply chain for takeback schemes. • Monitoring and measurement of parts recycled and refurbished., report back to the Scottish Government.	• Coordinate with owner/operators to strengthen industry decommissioning commitments • Commission Catapult Innovation and Research Centre to expand beyond offshore wind. • Incentivise and/or support hub to promote better maintenance and reuse practice

Table 7.1: Opportunities, risks and actions for circular economy-based decommissioning

			Recommended actions		
Opportunities	**Key considerations**	**Risks**	**Zero Waste Scotland**	**Industry**	**Scottish Government & Agencies**
Skills and Training	• Skills prioritisation. • Training and awareness planning. • Emergence of new material processing technology with strong links to Scotland (LifeBrio, 2017). • Current university cooperation with onshore wind industry. • Past operator and academic partnerships. • Existing complementary industries (electronic refurbishing).	• Potential absence of skills in Scotland. • Lower rates of onshore wind farm commissioning in recent past could result in skills shortages for decommissioning. • Competition for skilled labour from offshore wind decommissioning.	• Provide platform for industry/academia cooperation. Renewable Parts and Strathclyde University link demonstrates partnership potential. • Explore previous operator and academic partnerships to produce a roadmap to skills growth. • Revisit outcomes and investment potential for LifeBrio. • Skills study to identify guidance and capacity alongside key industry stakeholders.	• Donation of turbines to education for training. • Create a platform for adjacent industries to explore market opportunities. • Support apprenticeship and skills programmes that will support refurbishment and decommissioning. • Work with Academia to improve material selection based on disassembly; e.g., thermoset resins can be replaced with thermoplastics. • Work with Academia to improve material selection based on scarcity, e.g., balsa wood alternatives may be necessary for blades.	• Focus of National Renewables Infrastructure Plan or Low Carbon Renewables Enterprise Areas to onshore wind decommissioning. • Formation of and funding for academic research relating to onshore wind decommissioning. • LifeBrio investment opportunities. • Commission Catapult Innovation and Research Centre to expand beyond offshore wind.

Table 7.1: Opportunities, risks and actions for circular economy-based decommissioning

			Recommended actions		
Opportunities	**Key considerations**	**Risks**	**Zero Waste Scotland**	**Industry**	**Scottish Government & Agencies**
Suggested geographic location of future reprocessing infrastructure and storage locations	• Central hub requirements. • Size of the storage locations. • Location of market for reuse. • Metal reprocessing market in Scotland. • Mechanical and chemical processing infrastructure. • Pyrolysis processing plants exist/planned for Scotland; however, they are not set up to process fibreglass. • Ports across Scotland currently used for import processing of onshore and offshore turbines. • Material recycling, like fibreglass, is not an issue restricted to the wind industry.	• No dedicated infrastructure to dismantle, transport and process wind turbines. • Fibreglass processing is not present in Scotland. • Fibreglass processing not economical. • Takeback schemes abroad. • Potential shortage of cranes and transport vehicles.	• Study on existing infrastructure (cranes, transport, facilities, ports) to identify potential facilities for hub. • Facilitate cross industry review of material recycling capacity, demand for use and demand for output. • Business case for investment. • Transportation study to identify guidance and capacity alongside key industry actors.	• Engagement with OEMs in regard to licensed operators in Scotland to reduce transport, carbon, and material export in takeback schemes.	• Incentivise ports to respond to infrastructure needs through National Renewables Infrastructure Plan or Low Carbon Renewables Enterprise Areas. • Commitment towards investment in infrastructure such as decommissioning hubs, mechanical recycling technology/facilities. • Review of pyrolysis capacity in UK and investment for adaptation to new feedstocks. • Incentivisation for manufacturing, reprocessing, and recycling industries through policy and fiscal levers.

8. Task 7: Sector Engagement

8.1.1 Survey

8.1.1.1 Overview

A survey was developed using Microsoft forms and the questions were agreed with Zero Waste Scotland. The survey was distributed by Scottish Renewables via their March monthly newsletter. It was also shared by the Jacobs and ITP Energised project team with their onshore wind contacts and via LinkedIn. The questions asked are shown in Appendix 4 – Survey Questions and the responses have informed and corroborated the findings for Tasks 1-6 as detailed in Sections 2-7 of this report. Further details on the response are provided below.

Sixteen respondents completed the survey and were from the following roles within the onshore wind sector:

- Development – 3 respondents.
- Operations and Maintenance / Asset Owner – 7 respondents.
- Circular Economy Business – 2 respondents.
- Other – 4 respondents.

Further details of respondents have been anonymised within this report.

8.1.1.2 Results

As detailed in Section 3 (Task 2) a review of circular economy-based solutions from decommissioning of onshore wind turbines and their composite materials identified ten high-level options for use after decommissioning. The survey asked respondents to select the three circular economy-based solutions from the list of ten options that a) offer the most practical and that b) offer the most potential for efficient use of material resource during the decommissioning of onshore wind turbines in Scotland in the future. The numbers of votes that each potential option received is shown below in Table 8.1 below. The reuse of components as spares for wind turbines received the most votes for both the most practical solution and the most potential solution.

Table 8.1: Survey respondents votes for the most practical solution and the most potential solution for a list of ten potential options of varying circular economy potential

Potential options of varying circular economy potential	Votes for most practical solution	Votes for most potential solution
Reconditioned turbines for second use at a different site	10	8
Reuse of components as spares for wind turbines	11	10
Reuse of components and structures for non-wind turbine solutions in other sectors	7	6
Scrap metal recycling	5	5
Metal recycling through Electric Arc Furnace	1	2
Shredding and grinding of fibreglass materials for use in construction	4	6
Processing fibreglass through dry distillation (Pyrolysis) to produce fibres and oil	1	1
Thermal processing of fibreglass to produce clean fibres	0	1
Chemical depolymerisation of fibreglass to produce clean fibres	0	1
Energy recovery from incineration of materials	3	3

Respondents were asked if there are any additional circular economy based solutions for the reuse or repurposing that could be employed for components of onshore wind turbines, the responses are shown in Table 8.2 below.

Table 8.2: Respondents suggestions for circular economy-based solutions for the reuse or repurposing of onshore wind turbines

Suggestion number	Respondents suggestions for circular economy-based solutions for the reuse or repurposing of onshore wind turbines
1	Gearboxes could be refurbished domestically, and a market created for reuse. Large amounts of copper strip used for lightning protection must be recycled. Used gearbox oil will need to be reprocessed or properly disposed of.
2	Looking to provide a one stop shop to process the existing blades and to remove future wind turbines.
3	Recycling blades into children's playground toys and shade/shelter from sun and rain.
4	Redesign of materials and components of a wind turbine that reduce the actual material required/ footprint (for example thinner, smaller, lighter, single and more sustainable material types) used to make all the components of a wind turbine (this includes considering the location of development to enable smaller, lighter, thinner turbines) to be designed for a longer working life, decommissioning and break down to parts that can then follow the waste hierarchy (reuse, refurb, recycling, recovery and disposal).
5	Key WTG parts (nacelles, gearboxes, bearings, mechatronic equipment) donated to skills providers to ensure skills and training providers can provide quality technicians to the sector as it continues to grow.
6	Oils used could be recycled for energy via anaerobic digestion.
7	We believe in retrofitting and upgrading wind turbines for installation in new power generation projects, hydrogen generation, hybrid projects, and other projects.

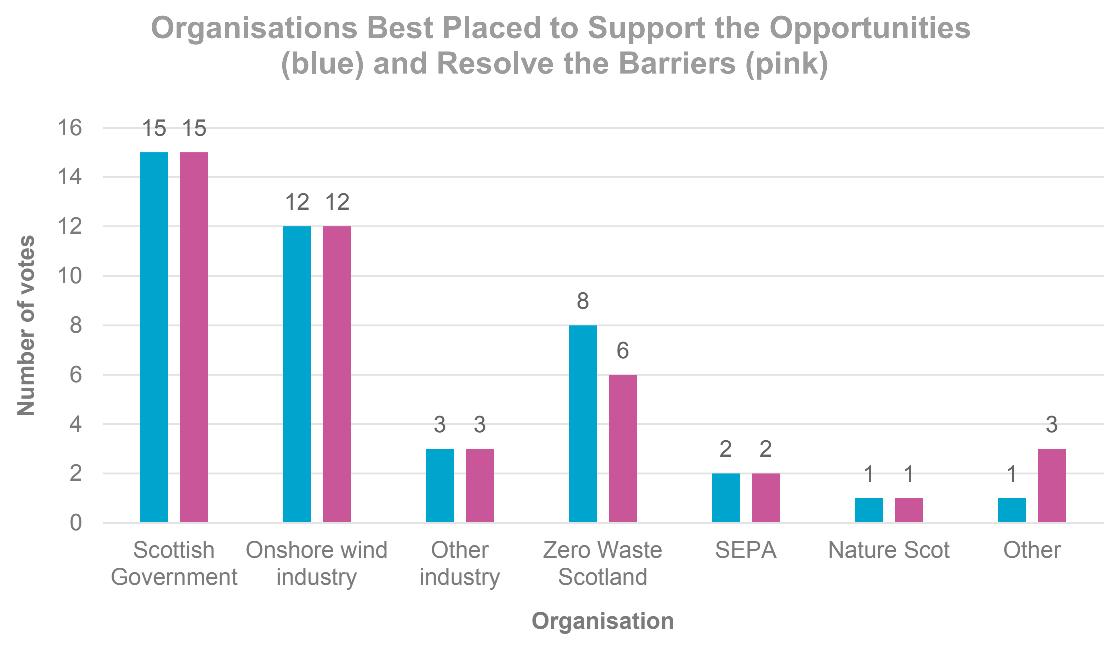
Based on the research presented in Section 7 (Task 6), participants were shown a list of key opportunities to develop circular decommissioning of onshore windfarms in Scotland and were asked to select a) the three **greatest opportunities** to develop circular decommissioning and b) three **significant barriers** towards implementing circular decommissioning of onshore windfarms. The responses are shown in Table 8.3 below.

Table 8.3: Survey respondents votes for greatest opportunity and significant barrier from list of key opportunities to develop circular decommissioning of onshore windfarms in Scotland

Key opportunities to develop circular decommissioning of onshore windfarms in Scotland	Votes for greatest opportunity	Votes for significant barriers
Amendments to the design of future assets – 'design for decommissioning'	10	5
Change in legislation/regulation/planning	8	7
Public and private sector investment	4	8
Commitments from owner/operator	5	9
Skills and training	2	0
Future reprocessing infrastructure and storage locations	14	11

The survey asked participants which organisations are **best placed to support the opportunities** identified above in Table 8.3 and also which organisations are **best placed to resolve the barriers**. The responses are shown in Figure 8.1 below and highlight that the industry see the Scottish Government and the industry themselves as best placed to support the opportunities along with Zero Waste Scotland.

Figure 8.1: Survey Respondents Votes for Organisations Best Placed to Support the Opportunities (blue) and Resolve the Barriers (pink)



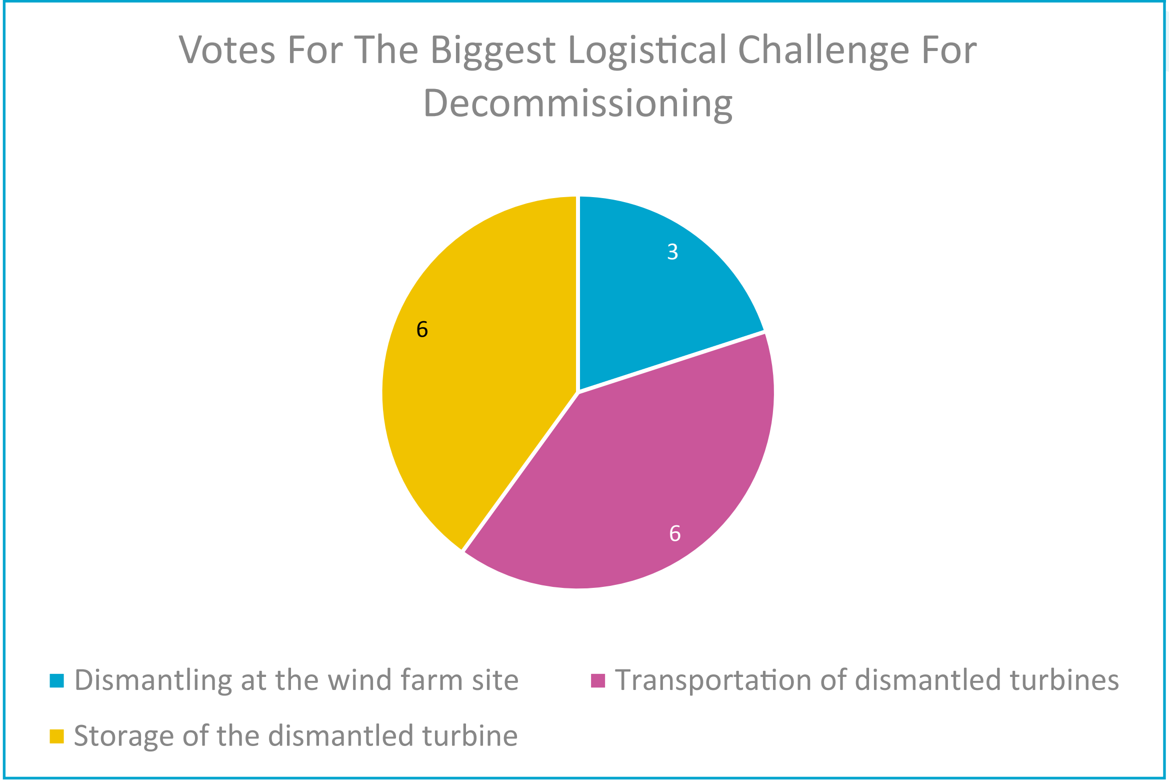
The respondents were asked what they think would be the most valuable market intervention to encourage more efficient processing of decommissioned onshore wind turbines in Scotland, the responses are shown in Table 8.4.

Table 8.4: Respondents suggestions most valuable market intervention

Suggestion number	Respondents suggestions
1	Incentives to promote reuse and refurb of major components such as gearboxes and generators. Subsidised development of a domestic steel reprocessing facility.
2	Creation of a secondary market to increase value of second-hand parts & recycled materials.
3	Commitments to available infrastructure.
4	In France they have legislated recently to ensure that a high % of turbines are recycled, we now build this into our models when buying sites.
5	Building and designing turbines so that they are able to be recycled easily. Fines and penalties for abandoning turbines and their components on green field sites.
6	A committed industry that gives the confidence to the market that material will be available and so they can invest - stimulate competition to supply a market.
7	Legislation can provide this investor confidence and level playing field but is often viewed negatively by industry and it would be great to see the sector driving this rather than having to be "forced" by legislation to make circular economy decisions. So, they are taking ownership of their materials and developments from cradle to grave and not just aiming to achieve a single objective of generating energy.
8	Change to feed-in tariff rules.
9	Section 75 planning agreements to encourage/force owner/operators to implement circular economy use at all times when decommissioning existing sites for the purposes of establishing next generation of WTGs.
10	Promotion of manufacturing, reprocessing, and recycling industries via various policy and fiscal levers to establish a robust supply chain would be important.
11	By repowering existing wind farms, it is possible to generate a new circular economy industry and create new jobs.
12	Government financial incentives to repower old wind farms.
13	A deep understanding of the 2nd hand turbine market and material re-purposing opportunities.

The survey also asked what respondents thought was the biggest logistical challenge for decommissioning and the results are presented in Figure 8.2 below.

Figure 8.2: Survey Respondents Votes for The Biggest Logistical Challenge for Decommissioning (please note that one respondent did not complete this question)



Lastly, the majority of respondents agreed with the assumptions that were used to develop the model (63% agreed, 25% disagreed and 13% did not respond), described above in Section 2 (Task 1). The feedback from the respondents who disagreed with the assumptions is presented in Table 8.5 along with how the assumptions were adjusted to consider their points.

Table 8.5: Respondents suggestions for updating the model assumptions

Feedback	Assumption Modifications (Task 1)
New consents are being sought for → 25 years. Review standard operational life assumptions and amend assumption of 25-year life accordingly	Life extension to 35 years is considered under assumptions 4d and 5e within the decommissioning forecast model.
There is no reference to the life extension of wind turbines	Life extension to 35 years is considered under assumptions 4d and 5e within the decommissioning forecast model.
The high case is too low, we are already looking at repowering sites after the tariff expires (10-15 yrs.), in the future we will certainly see older (windier) sites up for repowering much earlier than before, and certainly there will be few if any sites not ever repowered.	Assumption 5a, forecasting the high decommissioning scenario, was modified to consider early repowering at 15 years as follows: “5a. 25% of operational turbines are repowered after 15 years” With respect to the comment that be few if any sites not ever repowered, changing assumptions 4c, 4d, 5d and 5e, where it assumed sites may be decommissioned without repowering would not significantly affect the forecasts to 2050. If these sites were repowered, the existing turbines would still require

Table 8.5: Respondents suggestions for updating the model assumptions

Feedback	Assumption Modifications (Task 1)
	to be decommissioned. While it is recognised that those which would be repowered in the next 5-10 years may be decommissioned before 2050, this is considered to represent a very minor change to the forecasts and therefore the assumptions were not modified.
Assumption 2 is not valid: Any small-scale developments with three turbines or less at 0.5MW per turbine are assumed to be non-commercial developments and are not considered within the estimates. The medium wind sector is already very experienced with decommissioning, reuse, refurbishing turbines, repowering sites, parts replacement, and reuse, etc. We are currently looking after 100s of turbines over 30 years old still providing a commercial return and expect them to be working for at least another 15 years+. These sites could be made more efficient and have extended lives by allowing repowering with larger more efficient machines - if the FiT / planning rules were changed. These machines could come from decommissioned larger wind farms to allow the circular economy to be maintained. (NI is a good example of this already happening).	A previous iteration of assumption 2 was proposed that small scale developments with three turbines or less at 0.5MW per turbine were assumed to be non-commercial developments and were not considered within the estimates. The assumption was modified such that turbines between 100kW and 500kW are included in the forecasts. As noted in assumption 2, turbines with a capacity less than 100kW are not included within the RUK data and are therefore not considered within the estimates.

8.1.2 Interviews

8.1.2.1 Overview

In addition to the survey a number of interviews were held virtually over Microsoft teams with a series of onshore wind stakeholders involved across the lifecycle of onshore wind (i.e., development, OEM, O&M and circular businesses) to gather whole sector views. The organisations that were interviewed virtually are set out below with further details on the interviewees and a summary of the key points raised in Confidential Appendix 6 which is provided to ZWS only to anonymise responses.

An outline of the themes of questions asked during the interviews are set out in Appendix 5, although these were tailored depending on the interviewee and their role within the sector.

The feedback from the interviews has been used to inform and corroborate findings reporting in Tasks 1-6, presented in Sections 2-7 of this report.

SSE Renewables (https://www.sserenewables.com/)

SSE Renewables are a leading developer and operator of renewable energy across the UK and Ireland with nearly 2GW of operational onshore wind capacity and over 1GW under development.

Ventient Energy (https://www.ventientenergy.com/)

Ventient Energy is the largest independent, non-utility generator of onshore wind energy in Europe. They own 690MW of onshore wind in the UK across 34 wind farm sites.

Scottish Power Renewables (https://www.scottishpowerrenewables.com/)

Scottish Power Renewables (SPR) is part of the Scottish Power group of companies operating in the UK. SPR has over 40 operational windfarm sites producing over 2,500 MW.

Renewable Parts (https://www.renewable-parts.com/)

Renewable Parts is a leading supply chain and refurbishment specialist based on Scotland focusing on wind turbine parts.

Vestas (https://www.vestas.com/)

Vestas design, manufacture, install, and service wind turbines across the globe, and with over 132GW of wind turbines in 83 countries, Vestas have installed more wind power than anyone else. They also host the world's largest spare parts shop for wind turbines.

Spares in Motion (https://www.sparesinmotion.com/)
Spares in Motion is an e-business platform for the wind turbine aftermarket based in the Netherlands, Germany, Spain and the United States. They connect supply and demand for the wind turbine aftermarket and aim to optimise the use of resources.

9. Conclusions & Summary of Recommendations

To quantify the profile of onshore wind decommissioning in Scotland from the present (2021) to 2050 and to estimate the materials volumes generated from decommissioning, Jacobs undertook seven tasks. A summary of the key findings and main recommendations from each of these tasks is highlighted in Table 9.1 and the main recommendations for organisations is shown in Table 9.2.

Table 9.2 provides a summary of the key recommendations from each of the tasks presented in Sections 2 to 8 of the report.

Table 9.1: Summary of Main Conclusions

Task	Conclusions
Task 1 Decommissioned turbine estimates	Between 2021 and 2050, it is estimated that there are 4,894 number of turbines in Scotland that will be decommissioned in the low forecast and 5,613 number in the high forecast. The forecast demonstrates a significant case for dealing with decommissioning, but it requires refinement and monitoring to plan for the future.
Task 2 Circular Economy Options for materials and components	The MCA identifies that treatment options with higher resource efficiency, such as life extension, refurbishment and reuse, offer the greatest value to Scotland and the industry through economic growth and retention of resources and development of skills within the Scottish economy. The supply chain in Scotland for employing circular processes is a limiting factor. Similarly, the lack of recycling facilities to process fibreglass and resin-based waste streams is a barrier for value retention in Scotland.
Task 3 Value of options	A series of high level calculations concluded that the treatment options that employ greater resource efficiency offer the best potential return as measured financially and through GVA in Scotland.
Task 4 Carbon Impact of options	A comparison of emissions from waste treatment options was limited due to the BEIS waste emission factor methodology. However, calculations identify an approximate potential emission saving of 35% from manufacturing of wind turbines using recycled content compared to virgin materials. Assessment of emissions from transport of decommissioned turbines from each of Scotland's local authorities found that a port located on the central east coast would result in the lowest emissions.
Task 5 Process of storing and separating materials	Concern exists about the supply chains ability to respond to increased demand due to decommissioning; however, opportunities exist for decommissioning hubs in ports that have the potential space for equipment and infrastructure and may already have experience with the wind industry.
Task 6 Opportunities in moving to a circular approach to decommissioning	Limited infrastructure and supply chain's in Scotland are a limiting factor frustrating much of the industry's efforts to become more circular. Equally, design for decommissioning is seen as one of the most prominent needs for circular economy gains, but there is limited evidence that this is being addressed.
Task 7 Sector Engagement	Reconditioned turbines for second use at a different site, reuse of components as spares for wind turbines and reuse of components and structures for non-wind turbine solutions in other sectors were seen as offering the most practical solutions and the solution with the greatest potential. Future reprocessing infrastructure and storage locations is seen as the greatest opportunity and barrier to develop circular decommissioning of onshore windfarms in Scotland.

Table 9.2: Summary of Recommendations

Task	Recommendations
Task 1 Decommissioned turbine estimates	The decommissioning model should be refined to include more turbine model weights to more accurately predict the material flow. Decommissioning should be monitored to refine the predicted material flow.
Task 2 Circular Economy Options for materials and components	The MCA identified that value retention in Scotland and availability of infrastructure were consistent issues for more circular treatment options. Refurbished turbines are unlikely to remain in Scotland, and most scrap metal is exported abroad. Meanwhile, materials like fibreglass cannot be processed in Scotland and therefore require treatment abroad or landfill/energy recovery. As a result, support must be provided to the onshore wind decommissioning supply chain within Scotland to encourage treatment and/or reuse in Scotland.
Task 3 Value of options	The GVA calculations require expansion and refinement beyond disassembly and treatment to include more advanced material lifecycle phases. The cost/value per turbine should be recalculated according to any refinements to the decommissioning forecasting mode (Task 1).
Task 4 Carbon Impact of options	Consider how emissions from waste management options can better account for process emissions to facilitate better comparisons for end-of-life scenarios. Model refinements to consider production of zero-emissions freight vehicles.
Task 5 Process of storing and separating materials	Incentivise growth of supply chain for employing circular processes. Further study is required to identify the capacity and optimal location for decommissioning hub(s) at ports based upon decommissioning forecasts.
Task 6 Opportunities in moving to a circular approach to decommissioning	On the basis of the potential for a circular economy approach to decommissioning onshore wind turbines presented in this report, the following actions are identified for consideration. **Scottish Government:** • Support for a Scottish reuse, repair, and brokerage platform. • Create an onshore wind energy council to identify key legislative conditions and requirements for decommissioning. • Through NPF4, adoption of proactive development plan policies, supplementary guidance and the planning application process, support and facilitate proposals for recommissioning onshore wind turbines where the application can demonstrate low carbon use of materials or retention of existing materials and where these are consistent with wider spatial aims and policies in NPF4 and the local development plan. • Consider update to guidance on decommissioning plans to support retaining and re-using materials as an aim and outcome. • Legislate for recycling targets from turbines. • Introduce requirement for developers to supply material passports for components. • Identify or create the levers for investment – Green Investment Portfolio, National Investment Bank. • Encourage and incentivise internal Scottish market so decommissioned turbines are recommissioned in Scotland. • Incentivise market growth in novel recycling technology. • Incentivise market growth in novel use of turbine components. • Incentivise ports to respond to infrastructure needs. • Incentivise and/or invest in hub to promote better decommissioning, maintenance, and reuse practice • Funding for further academic research for onshore wind decommissioning and support for recommendations from existing research such as those being undertaken by Catapult and NCC. **Zero Waste Scotland:** • Collaborate with Scottish Renewables to coordinate industry partners to create a step-by-step framework for decommissioning in Scotland. • Align with cross industry studies into fibreglass disposal volumes and innovative recycling technology in Scotland. • Support the Scottish Government to explore the formation of an onshore wind energy council to identify key legislative conditions and requirements for decommissioning.

Table 9.2: Summary of Recommendations

Task	Recommendations
	• Review of market conditions considering Brexit. • Study to identify scale of market for SMEs; potential focus on opportunities for older turbine models where OEMs are more price sensitive in regard to maintenance. • Provide platform for industry/academia cooperation. • Skills study to identify guidance and capacity alongside key industry stakeholders. • Facilitate cross industry review of material recycling capacity, demand for use and demand for output. **Onshore Wind Industry:** • Review complexity of OEM part numbers and encourage transparency to improve ability to replace or recirculate components. • Validate decommissioning forecast model and output, providing further input on turbine model weight and material composition and anticipated decommissioning and repowering. • Review Scottish opportunities for resale of decommissioning turbines and components. • Lead dialogue with industry/owner operators on decommissioning process to facilitate planning and design changes, leading to recommendations for the Scottish Government. • Work with academia to improve material selection based on disassembly and/or scarcity. • Formulate industry-wide approach towards 'Right to Repair' legislation. • Align with cross industry studies into fibreglass disposal volumes and innovative recycling technology in Scotland. • Providing investment for new recoverable composites. • Identify investment opportunities or partnerships with Scottish tier 1 and 2 suppliers to develop local supply chains. • Link decommissioning to carbon reduction commitments. • OEM partnerships with Scottish tier 2 & 3 supply chain for takeback schemes. • Donation of turbines to education for training.
Task 7 Sector Engagement	• n/a

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