Beinn Ghlas Wind Farm

Outline Circular Decommissioning Strategy

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REBLADE

nadara

Document history

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Abbreviations

PCB	Printed Circuit Board
CDM	Construction design and management
CFRP	Carbon fibre reinforced polymer
CO_2	Carbon dioxide
CRMA	Critical raw materials act
CV	Calorific value
CWIC	Coalition for Wind Industry Circularity
EfW	Energy-from-waste
ESG	Environmental and Social Governance
EU	European Union
FIT	Feed-in Tariff
GFRP	Glass fibre reinforced polymer
GHG	Greenhouse Gas
GRP	Glass-reinforced plastic
GW	Gigawatt
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
MoU	Memorandum of Understanding
MW	Megawatt
NMIS	National Manufacturing Institute for Scotland
OEM	Original equipment manufacturer
STEM	Science, technology, engineering and mathematics

Executive summary

Nadara's commitment to circular decommissioning

Nadara is one of Europe's leading independent renewable energy generators, passionate about pioneering ways of working that enable the company to be a force for good that strives to positively impact people and communities and minimise its impact on the environment.

Nadara brings together 30 years of combined industry experience to become one of Europe's largest renewable energy IPPs (Independent Power Producers). Nadara has an operational 4GW portfolio of around 200 onshore wind, solar, biomass, and energy storage plants, including 23 onshore wind farms with an installed capacity of 768MW in Scotland. The company operates in Europe – notably in the UK, Italy, France, Spain and Portugal – and the US, and has more than 1,000 employees.

The company's success is recognised by the strong support of the pension funds that choose to invest in it. Their backing means Nadara can provide renewable energy to even more households and businesses, while ensuring a long-term financial return for the millions of people who trust it as a source of stable retirement income.

Nadara aims to lead the energy transition, investing in all the elements that are crucial for its implementation: renewable generation, electrification, energy efficiency and more flexible consumption, providing the energy solutions that produce a more sustainable energy system, using the extensive experience and skills of its team.

What differentiates Nadara is its duty of care towards colleagues, clients, the environment, and the communities within which it works.

As an organisation with sustainability at its core, Nadara is committed to minimising the impacts of its operations on the environment. As part of Nadara's wider approach to sustainability, circularity has been identified as one of the key areas of focus to deliver on this commitment. By focusing on circularity, this not only improves the efficient use of resources and reduces associated greenhouse gases but also supports the business achieving operational objectives. For example, at operational sites in the UK, Nadara is looking at ways to source second-hand parts, refurbish and reuse components wherever possible.

Through working with specialists, circular-focused supply chains and organisations such as Reblade, Nadara is actively supporting technological innovation to encourage the reuse of entire wind farm assets and their constituent parts for longer. Nadara has established, and continues to evolve, internal processes purposefully designed to promote resource efficiency and reduction and is fostering an internal culture that encourages a reuse, rethink and reduce approach to end-of-life wind farm resource management.

Nadara believes that there is a clear opportunity for wind farm decommissioning to be done in a more sustainable way. This is why one of the key objectives of the repowering project for its Beinn Ghlas Wind Farm (Beinn Ghlas) is to achieve maximum reuse and recyclability of wind farm components and materials.

The company is committed to adopting the following approach for the Beinn Ghlas repowering project:

- Identifying circular options for the decommissioning of existing wind farm parts, products and materials
- Committing to evolve internal processes that will help establish material traceability
- Taking a "no landfill" approach to end-of-life wind turbine blades
- Working with external experts and internal resource to plan in advance the processes, technical approach and material solutions for circular decommissioning
- Committing to wind farm decommissioning circularity by taking a Life Cycle Analysis (LCA) based approach to decision making to help create carbon savings
- Responsibly sourcing and encouraging circular-minded suppliers and contractors through tender and procurement practices
- Enabling positive stakeholder engagement and participation through all stages of development, construction and operation
- Ensuring circularity practice during construction and decommissioning site works
- Fostering circular-focused research and development, e.g. by supporting suppliers and contractors that innovate and find new methodologies that will help advance circularity within the sector
- Supporting the creation of circular jobs, skills and educational opportunities that will allow for long term sustainable employment within the local area as well as the wider region.

To highlight this commitment and to secure a sustainable, circular economy approach to decommissioning Beinn Ghlas, Nadara has established a partnership with Reblade, a company who are developing pioneering environmentally friendly wind farm derived material disposal methodologies through delivering circular innovation at scale. Nadara and Reblade are committed to developing a full circular decommissioning strategy that will build on the principles and commitments stated in this outline document. This ensures that the decommissioning of Beinn Ghlas aligns with circular economy, just transition and greenhouse gas emission reduction ambitions whilst creating economic growth through circular skills, jobs and supply chain opportunities in Scotland.

Planning for traceability and managing end-of-life blades

Wind turbines nearing the end of their lifespan present a significant recycling challenge, primarily due to the composition of their blades. While the steel components, readily recyclable due to the inherent value of scrap metal, find easy pathways back into the material stream, the glass fibre reinforced polymer (GFRP) and carbon fibre reinforced polymer (CFRP) found in the blades pose a much greater hurdle. These blades are accumulating in increasing quantities as wind farms are decommissioned, raising concerns due to the scarcity of viable and sustainable end-of-life solutions for this substantial volume of material. The sheer size and quantity of these discarded blades demand innovative approaches to create a truly circular economy for wind turbine components.

As the first generation of wind farms are repowered with larger more efficient turbines thereby contributing toward Scottish Government net zero targets, applying an achievable, circular focused Waste Hierarchy becomes critical. At Beinn Ghlas, Nadara is keen to understand the opportunities associated with the adoption of circularity best practices, such as the strict application of the Waste Hierarchy's principle of decision making which ranks waste management options according to what is best for the environment.

Nadara commits to ensuring the composite materials from Beinn Ghlas' end-of-life wind turbine blades and turbine nacelles are pushed towards the highest level of use on a self-imposed waste hierarchy. The blades decommissioned at Beinn Ghlas will be appraised in advance of decommissioning works to assess their viability for reuse and to ensure that the materials are not wasted during the decommissioning phase. Reuse and repurposing add value and represent a financially viable circular economy model for end-of-life wind turbine blades. They also save carbon, compared to other forms of linear disposal like shredding.

Highlighting the benefits of circular decommissioning

The decommissioning of Beinn Ghlas represents an ideal opportunity for Nadara to work with its stakeholders to investigate and implement innovative end-of-life circular solutions that have the potential to result in greater resource efficiency and lower environmental impact through a reduction in greenhouse gas emissions.

Further to this, by focusing on deploying circular principles during the decommissioning of Beinn Ghlas, Nadara has the opportunity to explore and test the commercial feasibility of such an approach, as well as the potential commercial opportunities that it may deliver.

Stakeholder engagement and public participation around circularity will ensure Beinn Ghlas continues to play a vital role in community wealth building as it reaches end-of-life and enters its decommissioning phase, achieving socioeconomic best practice.

Helping create a thriving economy through circular wind farm decommissioning is a great opportunity for local communities and the wider area surrounding Beinn Ghlas as well as planning for the delivery of renewable energy generation.

The future - what lies ahead?

In advance of any planned decommissioning works, Nadara commits to undertaking a fully circular-focused decommissioning approach to the planned decommissioning of Beinn Ghlas that will identify and map out optimal material circularity and reduce greenhouse gases from planning to onsite works and material solutions thereafter.

Forward planning of all decommissioning activities with a focus on delivering and capturing optimal circular focused material solutions presents the opportunity for Nadara to implement best practice for not only Beinn Ghlas but all of its onshore wind farms as and when they reach the decommissioning stage.

The environmental impact of wind farm decommissioning is a growing concern for both regulatory bodies and other interested parties. The decommissioning of Beinn Ghlas, coupled with the proposed repowering project, offers Nadara a valuable opportunity. This project allows Nadara to not only demonstrate the advantages of sustainable decommissioning practices for end-of-life wind farms, but also to ensure that local communities and stakeholders directly benefit from this new phase in the wind farm's lifecycle.

1. Wind farm decommissioning: an industry overview

1.1 Background

Wind power is recognised as a very important source of energy, combined with other clean energy generating sources such as solar power, and more wind farms and more powerful turbines can be expected in the drive to achieve net zero targets.

It is recognised that decommissioning wind farm assets and their associated components and infrastructure should allow for life extension (where practical), refurbishment, reuse and, if the technology exists, recycling. The evolving circular economy approach to wind farm decommissioning contrasts with traditional dismantling and material disposal methods of the past. Circularity offers optimal material management through cutting greenhouse gases and the use of virgin materials, as well as creating significant economic benefits, including the development of sustainable skills and jobs, and the growth of a circular economy supply chain.

Establishing and expanding a sustainable wind turbine decommissioning sector in Scotland requires sustained investment and a commitment to innovation. This includes supporting the development of new processes and technologies, as well as ongoing research and development projects, which are crucial for achieving a truly circular economy for wind turbine components.

1.2 Waste regulation

1.2.1 What is “waste”?

In many cases the question of whether something is waste or not is straightforward. If a substance, material or product has been discarded by its holder, or there is an intention or requirement to discard it, then it is clearly understood to be waste. The Scottish Environmental Protection Agency (SEPA) provides guidance on the factors that help decision makers define waste [Ref. 1], and refers to the Waste Framework Directive, a European Union directive that seeks to avoid waste generation and to use waste as a resource [Ref. 2].

The definition of waste is not clear when it comes to pollution control because the definition of waste is not necessarily synonymous with actual pollution or harm. A threat to the environment may arise due to the risk of pollution or harm caused by the waste being mishandled or abandoned, and the whole waste cycle requires regulating from the initial production of the waste through to its final management to ensure threats to the environment do not exist or are minimised.

1.2.2 The administration of waste management

Managing the production and disposal of waste is a significant environmental challenge, and a good example of mixed regulation. A range of mechanisms are used to address waste management, including producer responsibility which attempts to manage the causes of waste from its initial production to its final disposal.

The UK's approach to waste management is rapidly evolving, driven by several factors. Existing landfill sites are nearing capacity, and the scarcity of suitable new locations, coupled with the increasing distances required to transport waste, is prompting a shift towards more sustainable solutions. This evolving landscape is also being shaped by new initiatives and policies aimed at reducing landfill reliance.

Furthermore, evolving legislation, with its increasingly stringent targets for waste reduction, recycling, and recovery, is another key driver pushing the UK towards more sustainable waste management practices. The need to reduce landfill has been met with an increase in alternative recovery and recycling routes. There has also been a large increase in waste incineration capacity as well as economic instruments such as taxation and environmental permitting regulations.

While international waste regulations have traditionally focused on domestic waste management and preventing marine pollution (as exemplified by the UN Convention), a more comprehensive approach is emerging. European waste management policy, for instance, emphasises broader principles like the Waste Hierarchy (prioritising prevention, reuse, and recycling) and actively encourages the development of markets for recycled materials [Ref. 3]. This approach reflects a growing recognition of the need for a circular economy in waste management. The Waste Framework Directive sets out objectives and controls over waste in a general sense and establishes a set of high-level principles aimed at dealing with the management of waste.

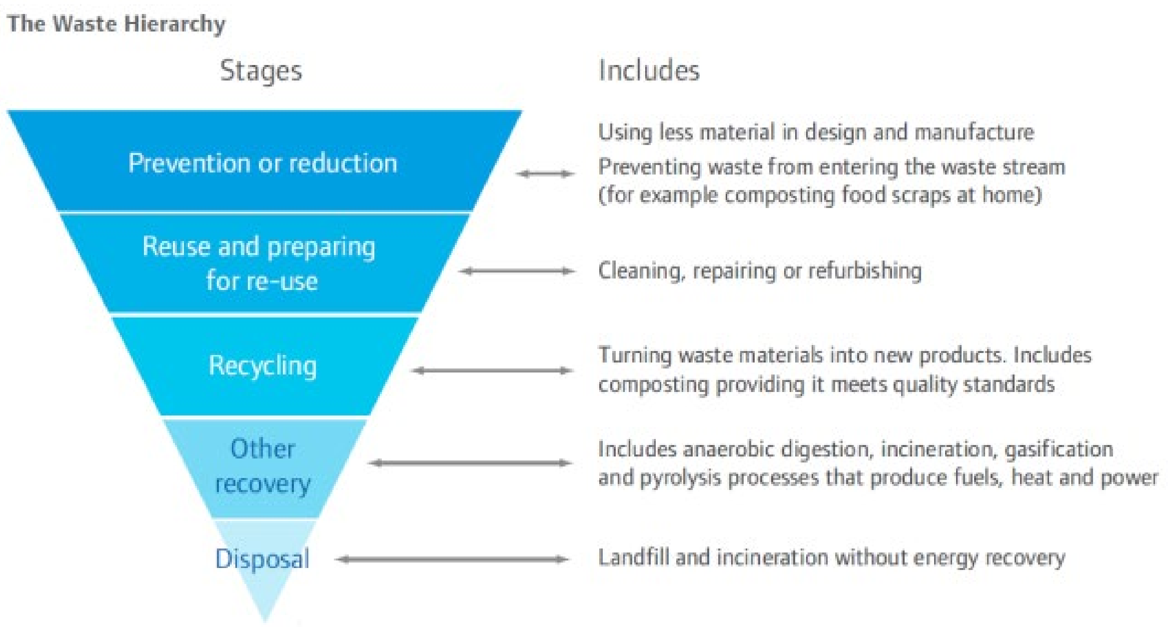
The key provisions of the Waste Framework Directive are:

- Without endangering human health and harming the environment
- Without risk to water, air, soil, plants or animals
- Without causing a nuisance through noise or odours
- Without adversely affecting the countryside or places of special interest.

1.2.3 The Waste Hierarchy

The Waste Hierarchy, illustrated in Figure 1, is the cornerstone of all waste law and has been used in UK policy and legislation since the 1990s. Its aim is to provide a hierarchy of waste with policies and laws designed to promote measures as high up the waste hierarchy as possible, with prevention at the top and sending waste to disposal the last resort. It is a legal requirement within the Waste Regulations for all producers of waste to take responsibility and reasonable actions to measure and apply the waste hierarchy in priority order.

Figure 1: The Waste Hierarchy



Reference: London Assembly (2017), [Ref. 3]

1.2.4 Prevention or reduction

The primary aim should be to prevent the creation of waste at source through design and process. This is linked to measurable initiatives such as LCA, clean technology and eco-labelling.

1.2.5 Reuse and preparing for reuse

Reuse is any operation by which any materials or components that are not waste are used again, and preparing for reuse relates to materials and components that can be un-wasted to enable them to be remanufactured, refurbished or reclaimed.

1.2.6 Recycling

Recycling is any recovery method where waste materials can be reprocessed and aims to keep products, materials and components at their highest value and utilisation. Where value is lost following recycling, this is referred to as downsizing, and where it is enhanced, is referred to as upcycling.

1.2.7 Recovery

Recovery methods include energy recovery where materials are sent for incineration.

1.2.8 Disposal

Disposal activities are methods of landfilling of waste, and the incineration of waste that does not recover energy from the waste.

1.3 Traditional decommissioning practices in the energy sector

Traditionally, command and control mechanisms outlined through the Waste Framework Directive have focused on the regulation of activities after waste has been produced and relied on a system not necessarily efficient when it comes to reducing waste and encouraging material reuse, recycling and recovery.

Consequently, there have been many grey areas that have led to uncertainty as to whether the difficult challenge of sustainable asset and related waste management has been addressed. These have included questions that can encourage waste minimisation, such as:

- Whether material which can be reused but is discarded can be classified as waste, for example something that still functions perfectly but is disposed of
- Whether material that is not wanted remains valuable to someone or something else
- Whether a residue or by-product from an industrial process that can be used as a replacement for a raw material should be classified as waste.

1.3.1 A traditional decommissioning approach.

The decommissioning of a wind farm involves rigorous planning, usually several years in advance of the actual works, with related works permits and approvals required to be in place through local authorities and relevant stakeholders prior to the decommissioning works commencing.

The rapid expansion of onshore wind energy in the 1990s and 2000s understandably prioritised operational efficiency. Consequently, decommissioning methodologies and processes, along with the management of resulting materials, were often assumed to be within the capabilities of existing contractors. Sustainable and circular practices in onshore wind decommissioning are a more recent focus. Historically, large-scale decommissioning efforts have primarily concentrated on recycling the steel from turbine components and towers, while other materials have received less attention.

With the first generation of wind farms rapidly reaching end-of-life and whole site decommissioning projects appearing, the industry is looking at sustainable solutions for the multiple material types arising from the decommissioning. Utilising previous 'traditional' methodologies and material solutions may not be optimal. Material from turbines that have had to be decommissioned early due to an unplanned failure or component swap out, have typically been destructively decommissioned and transported to either recycling facilities where a market value exists, or to landfill where there is no other satisfactory solution, particularly for wind turbine blades.

Landfill was a viable option when disposing of problematic materials including turbine blades and other composites, albeit it was not the best option. In the absence of legislation dictating otherwise, the option that provided an end-of-life waste solution was viewed as a satisfactory solution.

Typically, turbine blades were downsized on site to allow for practicalities of transportation and taken to landfill to be further downsized and buried. Turbine towers would be unbolted and reduced to individual sections for transportation to a recycling facility where the steel has a value, and only some of the components would be recycled or reused, however typically with limited options.

Foundations would be broken up using hydraulic hammers or explosives with the resulting material used throughout the site, and if the turbine wasn't required to be repowered, the site would either be restored to its original condition, or as agreed through planning conditions and/or land agreements.

Appendix 1 provides a general overview of a typical wind farm and its components, together with a summary of the key options currently being considered and appraised when assessing the decommissioning needs and end-of-life options for wind farm assets against the Waste Hierarchy Directive.

1.4 Carbon cutting, net zero & circularity in the wind energy sector

1.4.1 Producer responsibility

Producer responsibility and the growing emergence of Environmental and Social Governance (ESG) within organisations has created a positive cultural shift that is critically raising awareness for the sustainable management of the planet's resources whilst achieving net zero ambitions. Organisations are taking responsibility for materials and their whole lifecycle, including accounting for design to help support end-of-life recycling and focusing on reuse and recovery. Furthermore, organisations are now committing to imposing self-regulation through setting sustainability targets that are measurable, transparent and publicly reportable.

This approach is supported by SEPA, who have set out an objective to help facilitate in the delivery of a sustainable and low carbon economy through their guidance on life extension and decommissioning of onshore wind farms, a document that outlines a hierarchical framework aimed at reducing environmental impacts [Ref 4].

1.4.2 The International Organisation for Standardisation (ISO) Circular Economy Standards: 59000 Series

The new ISO Circular Economy 59000 series [Ref. 5] aims to support organisations in implementing a transition towards a circular economy and is considered important in the transition from a linear to a circular economy.

The series was released in May 2024 as a set of three standards as the foundational tools for enacting business circularity:

- ISO59004: Terminology, Principles and Guidance for Implementation
- ISO59010: Guidelines for the Transition of Business Models and Value Networks
- ISO59010: Measurement and Evaluation of Circularity.

They are standards specifically designed to foster a shift towards a circular economy, applicable to any type of organisation and offer practical guidance for taking steps towards sustainability and transitioning to a circular economy.

1.4.3 The European Union Critical Raw Materials Act (CRMA)

The CRMA [Ref. 6] is a regulation that aims to ensure a secure and sustainable supply of critical raw materials (CRMs) and was adopted by the European Commission in March 2023. The Act is considered essential for the European Union (EU) clean-tech economy to ensure access to all the critical materials for wind and steel, including rare earths, nickel, manganese, copper, aluminium, ferrous scrap and glass fibre fabrics. In summary, the Act supports the domestic production and refining capabilities for these materials and is designed to incentivise circularity and innovation. This is significant to the wind energy sector where steel represents one of the most tangible examples of circularity in decarbonisation and where access to other primary and secondary materials used in wind turbine production will be increasingly required.

1.4.4 The Onshore Wind Sector Deal (2023)

The Scottish Government Onshore Wind Sector Deal (2023) [Ref.7] sets out commitments from the onshore wind industry to deliver 20GW of onshore wind in Scotland by 2030. The Onshore Wind Sector Deal identifies the circular economy creating the opportunity for Scotland to be a world leader in material circularity. It takes cognition of the growing awareness of resource depletion and how this can be tackled through minimisation, reuse and the recovery of materials. This approach contrasts with the traditional management of waste in the sector and addresses the control of environmental risks from the disposal of end-of-life assets to address the opportunity of circularity.

1.4.5 The Coalition for Wind Industry Circularity (CWIC)

The CWIC [Ref. 8] was established in 2022 to help create and support a new, UK-based supply chain capable of moving towards a circular approach. The CWIC was initiated by the University of Strathclyde, National Manufacturing Institute for Scotland (NMIS), SSE Renewables and Renewable Parts Ltd with the aim of establishing a new UK-based industry, capable of moving towards a circular approach for replacing onshore wind components.

The ambition of CWIC is focused on ensuring wind turbine components do not end up as scrap through moving the industry towards a circular approach, a critical pathway to achieving net zero ambitions and supporting energy security. Further, it is recognised that circularity in the energy sector has the potential to create thousands of jobs and support economic growth in communities through local, home-grown supply chains.

1.5 Policies for a circular Scotland

1.5.1 Circular Economy (Scotland) Bill

The Scottish Government has committed to promoting the benefits of a circular economy and there are now a growing number of laws, regulations and approaches seeking to manage and minimise waste production, including producer responsibility legislation and measures to encourage reducing, reusing, recycling and the recovery of materials to help drive Scotland's circular economy.

In June 2023, Circular Economy Minister Lorna Slater published the Circular Economy Bill [Ref. 9] which proposed legislation that will give ministers the power to set targets to support the delivery of a circular economy in Scotland. The bill is now published and states "all parts of Scottish society" will have to "play their part" in building a more circular economy.[1]

The consultation on the Circular Economy (Scotland) Bill ended in March 2024 and, following Stage 2 amendments, the Circular Economy (Scotland) Bill was published by the Scottish Parliament on 26 June 2024. It outlines what the Scottish Government intends to do, by when and how it will operate to drive sustainable use and the management of resources. [2]

The Scottish Parliament's Net Zero, Energy and Transport Committee [Ref. 10] has stated in a report published in February 2024 [Ref. 11] that the Circular Economy Bill should "encourage behaviour change" and emphasised it should lead through education and awareness raising.[3]

1.5.2 Scotland's Circular Economy and Waste Route Map to 2030

The latest consultation was published in December 2024 [Ref. 10] and set out the Scottish Government's strategy to deliver national reuse and recycling targets. The actions outlined in the Route Map are designed to align with the actions outlined in the Circular Economy (Scotland) Bill to support an effective and localised approach to waste management and recycling across Scotland.

Key actions presented in the Route Map include a review and refresh of Scotland's Waste Data Strategy's action plan maintaining a program of research on waste prevention and related areas, developing public procurement opportunities to reduce environmental impact, and supporting the uptake of green skills, training, and development opportunities. These actions collectively aim to build a robust framework for a circular economy, encompassing data management, policy development, and skill enhancement.

1.5.3 Draft Energy Strategy and Just Transition Plan

These documents highlight the need to reduce, reuse, and repair materials to achieve a circular economy by 2023. The Draft Energy Strategy [Ref. 12] poses a crucial question about sustainably securing materials for energy infrastructure. The national planning framework aims to balance energy development with nature conservation, emphasising the need for a faster planning system to support the energy transition and circular economy material management facilities.

1.5.4 The Infrastructure Investment Plan

The Infrastructure Investment Plan [Ref.13] focuses on enabling the transition to net zero and sustainable growth, integrating community and energy transition activities, particularly around port infrastructure.

1.5.5 The Circularity Gap Report 2024

The Circularity Gap Report is an annual publication by Circle Economy [Ref. 14] which provides a metric to measure the circular state of the world economy.

According to the Circularity Gap Report, Scotland's economy was only 1.3% circular. This means that Scotland is almost completely reliant on the use of virgin materials which is in stark comparison to the Netherlands whose economy is about 25% circular.

The 2024 report highlighted opportunities to cut resource use in Scotland to bring its circularity to 11.8% and addresses seven areas of improvement, including the circular decommissioning of Scotland's energy infrastructure.

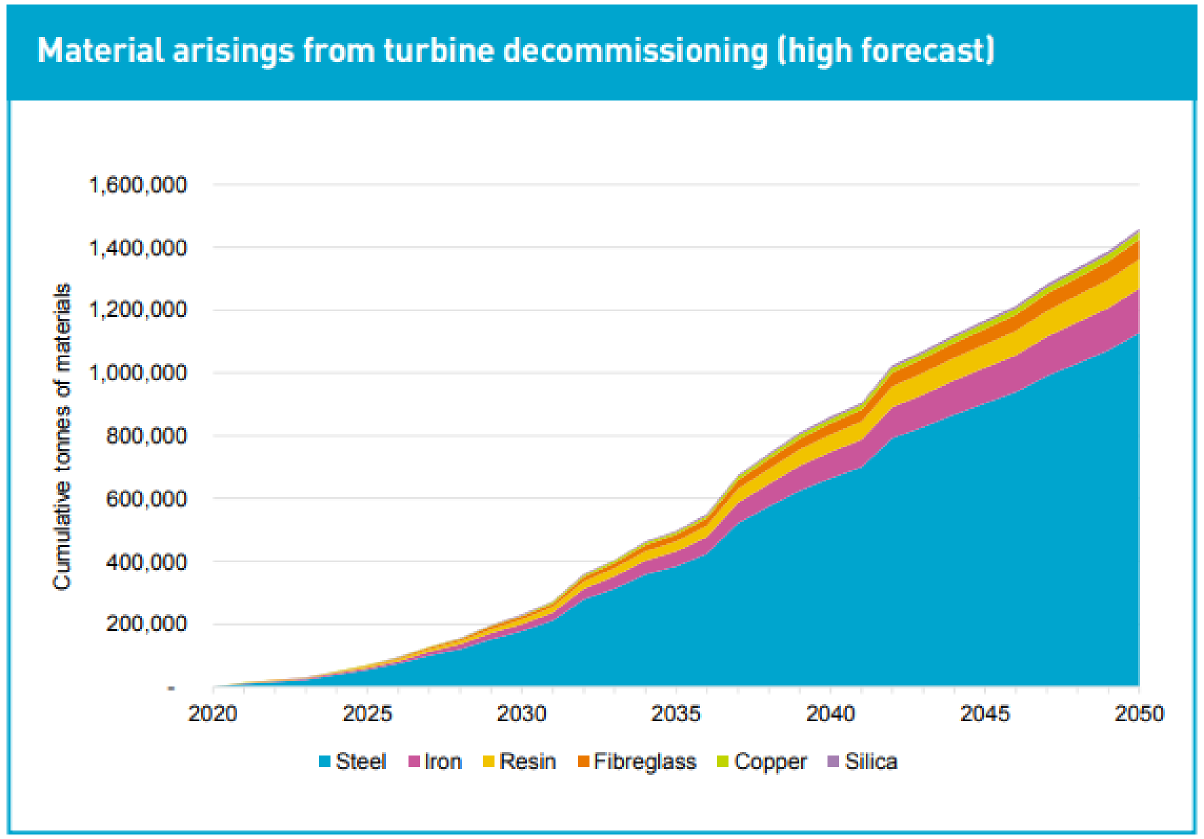
1.5.6 Zero Waste Scotland: The Future of Onshore Wind Decommissioning in Scotland

In 2021, Zero Waste Scotland published a report titled the Future of Onshore Wind Decommissioning in Scotland [Ref. 15].

[1] The Scottish Circular Economy Bill became an Act on the 8TH of August 2024.
[2] Scotland's circular economy and waste route map to 2030 "Sets an ambitious plan to deliver 11 priority actions that will help us maximise progress towards a circular economy. It is the product of extensive collaboration and engagement with consistently high levels of support since 2022"
[3] The Scottish NZET Committee lays out why the circular economy bill is so important and the wider impacts and benefits forging a strengthened circular economy brings to Scotland.

The report highlighted the materials that could be available prior to decommissioning, (Figure 2), and assessed circular options for end-of-life assets that could offer the greatest value at the lowest carbon value. Embodied carbon savings through reuse and using recycled content were identified to have reduced carbon impacts and to safeguard against future shortages of critical materials.

Figure 2: Wind turbine materials forecast



Reference: Zero Waste Scotland (2023), [Ref. 15].

In summary, the report states that the lifespan of current wind turbines should be maximised as far as possible, with reuse and refurbishment prioritised. Where reuse and refurbishment are not options, materials should be recycled with components refurbished for spare parts. Steel, iron, cast iron and copper can be readily recycled at end-of-life and can offset greenhouse gases by around 35% if used in the remanufacturing of new turbines in place of raw materials.

It is recognised that there is extremely limited data available to confirm the actual disposal or recycling destination of materials arising from decommissioned wind farm assets to date and that maximising the value of the materials within existing turbines is essential to reduce greenhouse gases and secure critical materials.

Zero Waste Scotland is undertaking a review of this report with an aim to quantify the landscape of onshore wind decommissioning in Scotland. The update will include a review of the innovation and critical raw materials relevant to onshore wind decommissioning and the economy of Scotland.

Zero Waste Scotland recognises there are significant opportunities for a circular economy through the reuse, refurbishment, and repurposing of components and materials, however, also recognises that current data on the scale of the onshore decommissioning market in Scotland is limited.

Zero Waste Scotland's initial estimates indicate approximately 800 onshore wind turbines in Scotland will approach the end of their operational life by 2030, with previous estimations that more than £70 million could be added to the end-of-life asset value of key materials operating within Scotland's renewables sector.

Zero Waste Scotland highlights that embracing a circular economy for decommissioned wind turbines presents an opportunity to lower greenhouse gases, enhance material management, create skills and job opportunities, and contribute to the Scottish economy.

2. Beinn Ghlas Wind Farm: outline schedule of circular decommissioning

2.1 Nadara's commitment to circular decommissioning

2.1.1 Beinn Ghlas – overview

The 14 Bonus B44/600 turbines of Beinn Ghlas in Argyll, Scotland have a total installed capacity of 8.4 megawatts (MW) of electricity, enough to power around 7,002[4] homes annually. Located approximately 12km south-east of Oban, it was one of the first large-scale wind farms to commence operations in 1999.

Beinn Ghlas continues to operate efficiently with technical analysis of the wind turbines demonstrating that they can continue to operate beyond their original design life. Beinn Ghlas secured planning consent to operate until 2033 following a life extension planning application in 2021 to extend the original planning consent expiry date.

Two principal considerations typically influence the decommissioning of a wind farm: the advantages offered by repowering with turbines incorporating the latest technological advancements, and the diminished performance and increased maintenance requirements resulting from the degradation of existing assets.

Beinn Ghlas will in due course require decommissioning and, subject to planning consent, be repowered. This would entail the dismantling and removal of the existing first-generation turbines and associated infrastructure, followed by the installation of modern turbines to enhance the site's efficiency and power output. The timescales to decommission the existing wind farm assets and to construct the repowered wind farm are programmed to take place post 2030 and could take around 23 months to complete.

Whilst Nadara will strive to prioritise the highest levels of the Waste Management Hierarchy for all materials resulting from the decommissioning of Beinn Ghlas, it also recognises that the Bonus 44/600 turbines represent older technology. As such, the demand for whole turbines or individual components will likely be limited, providing reuse solutions for only a small portion of the materials.

Significant socioeconomic benefits will accrue from informed sustainable decommissioning, notably the utilisation of local supply chains, the creation of skilled employment opportunities within sustainable supply chains and use of local infrastructure, such as tourism and work-related suppliers for external tier one and two suppliers.

2.2 Memorandum of Understanding (MoU)

Nadara[5] and Reblade, the first specialist wind turbine decommissioning service in the UK, have signed an MoU[6] committing to the design and implementation of a circular decommissioning strategy for Beinn Ghlas.

Working together, the MoU commits to ensuring that the circular decommissioning of Beinn Ghlas will be aligned with circular economy drivers of change and the Just Transition and net zero ambitions of stakeholders, policy makers, and of Nadara itself.

The MoU further commits to supporting the creation of circular supply chain opportunities, circular jobs & skills and education, with emphasis on Argyll and Bute, the wider Scottish Highlands and overall, the Scottish economy.

The MoU also confirms Nadara's commitment to applying circular economy solutions throughout the lifecycle upon consent and operation of the proposed Beinn Ghlas repowering project.

2.3 Optimising energy production prior to decommissioning

The implementation of inspection and maintenance activities at Beinn Ghlas is managed by specialist asset managers possessing significant expertise in wind turbine technology. This ensures the timely and efficient operational maintenance of the assets. Continuous on-site performance monitoring, coupled with a regime of monthly and annual audits, guarantees the optimal delivery of the maintenance programme and the ongoing safe and efficient operation of the facility.

As wind turbines begin to age, they can encounter operational challenges due to the stresses endured through operating for decades in all weather conditions.

The wind turbines at Beinn Ghlas will continue to generate a significant amount of renewable energy between now and decommissioning and their operational performance will be maintained through dedicated routine inspections, site maintenance and any necessary repairs. Nadara's operations and maintenance strategies ensure the wind farm will continue to convert as much wind into renewable energy as possible before it is decommissioned. Nadara's operational optimisation approach aims to reduce any losses in renewable energy production, therefore maximising energy production during the operational lifespan of the asset.

2.4 Committing to traceability & circular reporting

Nadara has committed to utilising the company's knowledge and industry expertise to set objectives that will support finding practical and meaningful ways to trace Beinn

[4] Source: RenewableUK Wind Energy Statistics – Homes Powered Equivalent, available here: https://www.renewableuk.com/energypulse/ukwed/#:~:text=Homes%20Powered%20Equivalent&text=RenewableUK%20calculates%20homes%20powered%20as,electricity%20consumption%20expressed%20in%20MWh..

[5] Formerly Ventient Energy: https://nadara.com/media-centre/renantis-and-ventient-energy-to-combine-to-form-leading-renewables-firm/

[6] The MoU was signed by Beaufort Wind Ltd, a wholly owned company of Nadara.

Ghlas derived materials where possible and to encourage circular reporting. This approach will help to increase knowledge and uptake of material circularity in the renewable energy sector and measure carbon production and mitigation measures arising because of onsite and offsite works.

As an influential industry asset owner, Nadara will work to support data-informed decision pathways to quantify the impacts and outcomes of asset decommissioning works and material destinations at end-of-life. A people-centred approach to encourage behavioural change within decommissioning will be supported through project planning and procurement activities to help reduce and eliminate destructive approaches, informed and driven by adopting transparent and clear reporting systems.

2.5 Planning & forecasting for circular decommissioning

In accordance with its commitment to responsible wind farm operation, Nadara will conduct a pre-decommissioning assessment of the turbines, the site infrastructure and resultant materials at Beinn Ghlas. This assessment will serve to identify the optimal circular economy options available at the time of decommissioning, which will be implemented to the extent practically feasible.

To ensure the implementation of optimal site works and circular solutions at Beinn Ghlas, a comprehensive understanding of site-specific downsizing and removal methodologies, available contractor skill sets, and suitable material solutions is required throughout both the planning and implementation of the entire decommissioning process.

Examples of current circular decommissioning options that may be suitable for Beinn Ghlas could include the following:

- Reconditioning of decommissioned wind turbines for second life use at a different site
- Reusing wind turbine components as spares for other wind farms
- Reusing components and other structures for non-wind farm solutions for use in other sectors
- Metal recycling
- GFRP and CFRP material processing through early-stage recycling methodologies, where practical, to support technological readiness levels, such as shredding and grinding for reuse in construction, pyrolysis, and chemical depolymerisation
- Reusing reinforced concrete bases, where practical
- Use of existing tracks for the repowered wind farm and/or agricultural purposes

Nadara's plans for the decommissioning of Beinn Ghlas will be examined and revised on a periodic basis through the following principles and justification, including but not limited to:

Evolving approach

The early instances of circular decommissioning strategies are not prescriptive. They can change as technology develops, new evidence emerges, and best practice matures. This demonstrates an ongoing commitment to up-to-date thinking.

Practical solutions

The emphasis on ‘practical solutions’ recognises that optimal circular economy solutions need to be weighed against what is practically achievable. Feasibility, affordability, and logistics will all be considered when deciding on the approaches taken.

Optimal and sustainable

The aim is to deliver the ‘optimal and sustainable’ decommissioning of Beinn Ghlas. This is to secure the best combination of environmental protection, economic sustainability, and social responsibility.

Stakeholder consultation

Most importantly, Nadara commits to a wider consultation with appropriate key stakeholders close to the start of decommissioning works with the focus on local consultation and making local concerns and expertise part of the final decommissioning plan.

2.6 Ensuring circular practices during Beinn Ghlas site works

2.6.1 Broad circular principles

Nadara is positioning the decommissioning and repowering of Beinn Ghlas as a flagship project, demonstrating leadership in circular economy practices within the wind energy sector. Nadara is committed to working with partners who share their vision and can deliver technically sound solutions while minimising environmental impact and staying within the procurement budget.

From planning to purchasing and on-site activity management, Nadara will look to apply the following general principles (although not solely):

Diverse service providers

There could be multiple specialists involved in dismantling and removing wind turbines and infrastructure. This recognises the nature of work and the requirement for varied expertise.

Partnership and collaboration

Nadara will endeavour to engage in partnership with Reblade and other specially selected partners, with a focus on collaboration to achieve technical excellence within budget. This implies the need for cooperation and common goals.

<u>Procurement focused on circularity</u>

Nadara will look to focus on circular-focused procurement methodologies where practical. This approach focuses on suppliers that have best-in-class circular practices themselves and encourages other suppliers to practice sustainable methods.

<u>Blueprint to evolving best practice</u>

Nadara aims to draw on the approach to decommissioning and repowering Beinn Ghlas as a blueprint and proof to the wider industry that demonstrates onshore wind farm decommissioning is possible in circular terms, measuring against safety, on-time performance, budgeting, and ultimately curbing additional greenhouse gases.

2.6.2 Reuse of Beinn Ghlas assets

The sale and reuse of Beinn Ghlas turbines and associated infrastructure could present a viable solution for the resulting material following the onsite decommissioning works. It will be unlikely that all 14 turbines could be sold as entire turbines due to industry drivers of change and asset suitability.

Nadara will liaise internally and externally with owners of Bonus B44/600 turbines to ascertain the demand for entire turbines and/or components arising from the decommissioning of Beinn Ghlas and look to utilise this solution where practical.

2.6.3 Transportation methodologies

To minimise carbon emissions due to fuel consumption, smart planning for transport should be employed in the decommissioning strategy. The transport plan must consider downsizing and circular activities to effectively reduce repeat movements around site and beyond. For example, minimising the need for escorted loads can greatly reduce the number of vehicles required during component removal and this can be achieved by ensuring transport loads stay below the maximum of 2.9m wide where practical.

Materials should be assessed in detail to understand the optimal loading strategies, and this may include downsizing blades, nacelles or tower sections. Understanding the best combinations of each component to get the most amount of material off site safely is also key to reducing greenhouse gases.

Where practical, the use of local transport suppliers could be a viable methodology for minimising greenhouse gases during transportation and indeed throughout the entire scope of works.

2.7 Committing to circularity through an LCA approach

2.7.1 LCA

Nadara recognises that by taking an LCA-focused approach to decommissioning, negative environmental impacts can be minimised through reducing greenhouse gas emissions and reducing the consumption of natural resources.

Life cycle analysis is a methodology that can be used to quantify the environmental impact of a product or a service throughout all or selected stages of its lifecycle.

The key stages of an LCA are illustrated on Figure 3 below:

Figure 3: A typical product/service lifecycle

Reference: Composites UK/National Composites Centre (2022) [Ref. 16].

By calculating the carbon impact of each material or process used throughout the life of a product or service, it is possible to highlight areas of improvement and compare avenues for the optimal carbon solution.

LCAs take an accumulation of many environmental factors of using a material or process and quantify this with an aggregated value of the tonnes of carbon dioxide

(CO_2) equivalent that this represents. By using a global figure, it makes comparing the environmental impact of two items much easier. CO_2 equivalent considers the cost to human health, ecotoxicity, resource depletion and carbon footprint.

2.7.2 A 'traffic lights' approach to Beinn Ghlas material management

Where practical and where there is existing and/or scalable new material solutions Nadara commits to a 'no landfill' policy for all materials resulting from Beinn Ghlas' decommissioning.

Nadara will seek to commit to a sustainable approach to Beinn Ghlas decommissioning using the following (but not limited to) principles of optimal material solutions:

- Relife
- Reuse
- Recycle
- Recover.

To optimise the circularity potential of Beinn Ghlas during the decommissioning works, Nadara deems it essential to possess comprehensive knowledge of Beinn Ghlas' component parts, their condition, and their potential circular decommissioning options. Nadara proposes to achieve this through the utilisation of its expert in-house resources and external contractors, drawing upon the combined input from the sustainability, procurement, asset management, and operational teams.

Furthermore, Nadara will engage with circular-focused decommissioning service providers and advisors to help formulate both business-wide decommissioning strategies and specific site decommissioning plans.

Prior to any on-site dismantling & material handling, Nadara will look to ensure Beinn Ghlas is thoroughly assessed to identify where possible materials can be managed optimally. This approach will maximise the potential for handling material as a resource and not as waste.

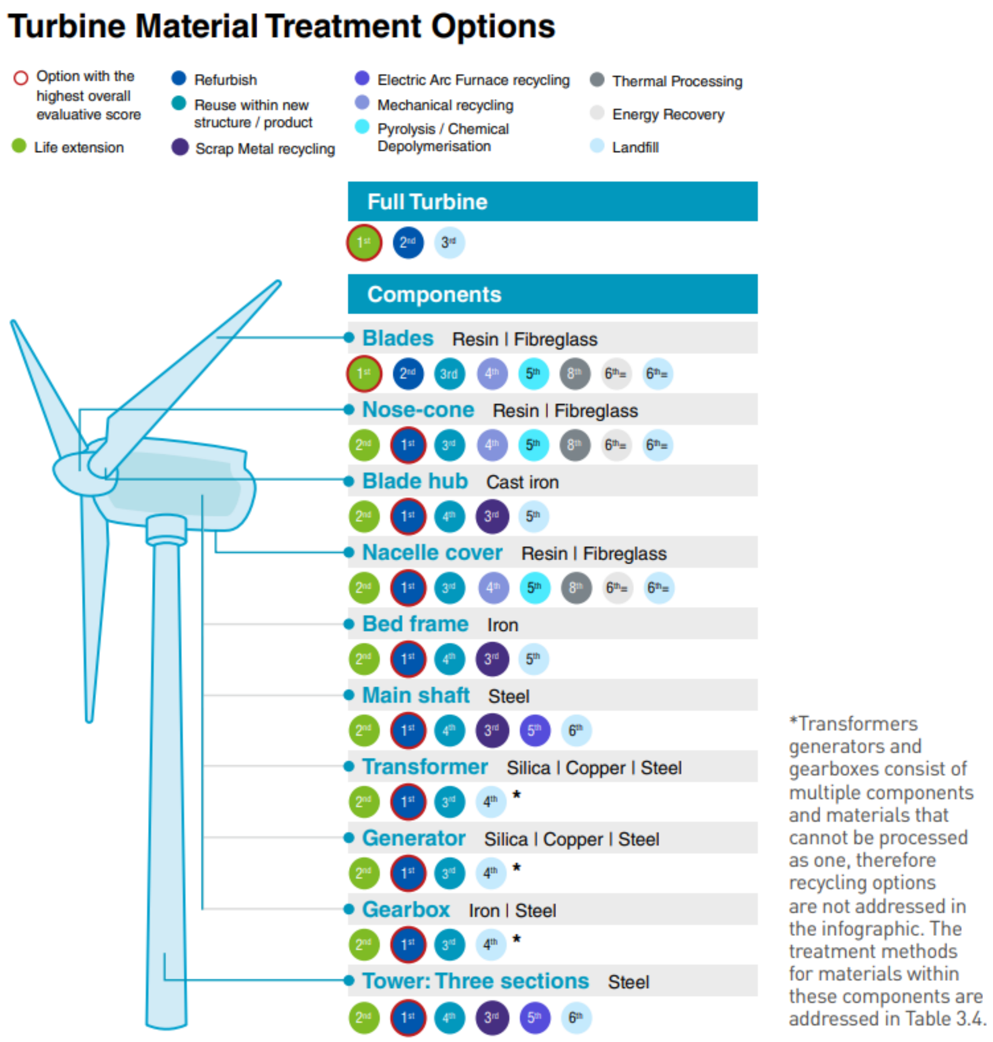
The turbine towers, which are made of steel, are expected to make up the maximum tonnage of materials recycled from Beinn Ghlas. Raw steel accounts for around three quarters of greenhouse gases during wind farm construction, therefore it is recognised that steel could have the most potential for carbon savings.

Beinn Ghlas derived GFRP and CFRP will be decommissioned and managed using the most viable solutions available at the time of the decommissioning.

Due to the increasing focus on end-of-life composites, it is believed that blade-focused material solutions currently being devised such as thermal and chemical-based solutions will have been proven and technically available at the scale required. Nadara will, where practical, also look to utilise some of the blades to make useful public realm infrastructure to help accelerate and promote innovative and carbon friendly solutions for end-of-life wind farm derived materials.

This approach is in alignment with the principles and guidance contained within Zero Waste Scotland's Onshore Wind Decommissioning in Scotland report (currently under consultation review for a further update) that concludes, where possible, a multi-criteria analysis should be undertaken to maximise resource use, outlined below in Figure. 4.

Figure 4: Turbine material treatment options



Reference: Zero Waste Scotland (2023) [15].

2.7.3 Steel and other metals

Steel and other metals derived from end-of-life wind turbines are easier to manage in that they hold substantial residual value as a major global commodity.

An LCA for steel material could focus on the downsizing of large steel components (electric arc or thermal methods) and transport to suitable steel recyclers.

2.8 Identifying the optimal sustainable options for Beinn Ghlas decommissioned parts, products and materials

2.8.1 Nadara's approach to Bonus B44/600 turbines at Beinn Ghlas

Nadara's general approach to material solutions for the Bonus B44/600 turbines is to maximise sustainability and circularity whilst maintaining a realistic approach regarding an aging turbine technology. The largely obsolete B44/600 may restrict the benefits of some refurbishment and reuse options. Nadara will still use best endeavours to ensure that any opportunities in this realm are taken as, typically, refurbishment and reuse options, specifically regarding turbine components, are the optimal solution with regards to carbon positive outcomes.

2.8.2 Towers

The towers of the Bonus B44/600 weigh up to 57 metric tonnes, at a height of 35m to hub. The towers are of a conical steel tube construction with painted corrosion protection.

The simple and effective method for sustainably dealing with the towers would be to downsize into sections (typically 2 or 3) and recycle at an oversize steel recycling plant. Metal and steel recycling is a mature industry, and this solution is typically financially viable and minimises additional greenhouse gas production.

At the time of decommissioning, the fluctuating price of recycled steel and other market factors will be considered to manage and optimise when the towers and other steel components could be locally processed. However, the main factor for sustainability is to reduce transportation and handling so this may not be realistic at the time of decommissioning and should only be used in extreme circumstances where the steel prices are down.

The optimal solution could be to analyse Beinn Ghlas' proximity to metal scrap dealerships and then choose options that allow for minimal transportation times and who has the appropriate yard space and machinery to accommodate large sections of oversized steel.

The Beinn Ghlas tower sections will be efficiently downsized to facilitate transportation to relevant metal recyclers. This process also minimises traffic disruption as the loads will be within acceptable sizes.

2.8.3 Nacelles and internal components

A major consideration for the nacelle material solutions is looking at the turbine type and specifically looking ahead to 2030 and the landscape in the UK for sub megawatt machines in the wind sector.

The turbines at Beinn Ghlas are very low output compared to today's standards, and with larger turbine models, such as V80s (>2MW) being decommissioned in Europe, it is difficult to see a market where refurbished B44/600s will be used in large portfolios.

Nadara will assess each component arising from Beinn Ghlas and, where practical, look to use relevant components through the remainder of its fleet should they be interchangeable.

Nadara will also look to assess the market for the sale of components to other owner/operators should there be a demand.

The nacelles typically weigh around 22.5 metric tonnes. The construction of the nacelles is a combination of metal components such as the bed plate and structural elements and composite spinner covers and rear plates.

The metal structural elements and internal components will be primarily made of basic metals such as steel and copper. These elements are easy to recycle, much like the tower sections.

The composite materials from the nacelles can potentially be recycled as there is limited usage in reuse or repurposing. This will be explored with the available options closer to the time of decommissioning.

2.8.4 Blades

Resins and fibreglass materials are expected to make up a significant tonnage of materials being decommissioned at Beinn Ghlas and are anticipated to present technical challenges when assessing options for end-of-life management.

Nadara is committed to sourcing and implementing the most optimal solution for wind turbine blades alongside other wind farm derived glass/carbon fibre materials.

An important note is that the LM 19.1 blades used on this turbine have a stall tip construction, which will likely comprise of steel and carbon fibre components. There may also be carbon strengthening throughout the blade which will have to be considered. Removal techniques can be employed for the carbon elements during downsizing if recycling is required.

Figure 5 summarises the value of wind turbine blade decommissioning when undergoing various end-of-life repurposing and recycling processes.

The graded traffic light scale is from worst to best. Fibres are deemed to have:

- No value in landfill or Energy-from-Waste (red)
- Low value as cement feedstock (orange)
- Mid-value when thermally or mechanically recycled, which leads to some fibre damage (yellow)
- More value in chemical recycling where fibres could be relatively undamaged but still need processing into intermediate material forms (yellow green)
- Most value when retained in the matrix for refurbishment/repurposing (green).

The 'Energy Use' column indicates the energy intensity level required to undertake each process, with chemical recycling having the worst impact.

Figure 5: Comparison of reuse and recycling for GFRP from wind turbines

Reference: Reblade.

Some material value for resin is indicated where it is used as filler (mechanical recycling), or chemicals are recovered. The flame indicates resin is burnt and energy is recovered.

Energy use is a combination of energy for downsizing plus process energy required. Thermal processes are assumed here to be powered by recovering the resin energy, though there is still further energy needed for fibre processing into intermediates.

2.8.5 Auxiliary components

It's important to be cognisant of the infrastructure components and their material role in decommissioning and repowering. There are many additional elements that play key roles in wind farms and due care is necessary to approach the best end-of-life solutions.

Foundations, roads and crane pads and the subsequent material solutions for them will be carefully assessed based on material, reuse and carbon emissions involved with any removal works and material destinations. Liaison with landowners and statutory stakeholders will be critical to ensure any infrastructure of use to others over and above Nadara for agricultural and/or recreational use will be factored into agreed removal methodologies and material destinations.

Foundations

Repurposing wind turbine foundations presents a significant challenge. The immense stresses that foundations endure during operation, coupled with the evolving specifications of new turbine technology can preclude their reuse. Further, the typically higher load demands of modern turbines make it difficult to certify existing foundations for new turbines. While complete reuse is often impractical, research into innovative foundation designs and repowering strategies may offer future solutions. Even if the entire foundation cannot be repurposed, the constituent materials, such as concrete and steel, can often be recycled, contributing to a more sustainable lifecycle.

At Beinn Ghlas, it is expected that the foundations will be removed to a depth of 0.5 metres, the rebar removed for recycling, and the concrete crushed and stockpiled for use during the repowering construction phase. This approach to foundation removal is considered to be the most appropriate method currently; however, subject to the regulatory planning requirements for Beinn Ghlas and emerging best practice, it will be reviewed nearer to the time of decommissioning.

Cables

The cables currently in use at Beinn Ghlas are not likely to be suitable for the increased capacity of modern turbines and new cables are expected to be installed as part of any repowering works on site. Closer to the time of decommissioning, Nadara will reassess the practicalities of removing old cables based on location, carbon impact of any cable removal works and demand for used cable.

Site roads and crane pads

Some or all the current roads may have to be altered for decommissioning and/or repowering works due to the size of cranes and other construction machinery required. The proposed repowering project will use existing wind farm tracks where possible with new sections of access track and upgrade works required to access certain infrastructure locations. For site roads and crane pads no longer needed, there may be scope for the material to be reused for these new roads as part of any repowering construction works.

Oil

Old oil from turbines is no longer considered waste by EU legislation and is now considered a valuable resource that can be purified and used again. This oil is used in the turbines in hydraulics and lubricants for moving parts such as the rotor and yaw bearings. The recycled oil can be reused on turbines and Nadara will endeavour to reuse any suitable recycled oil from the Beinn Ghlas turbines.

Small electronics

Depending on the component makeup of the B44/600s, there may be value in stripping the control boxes in the turbine bases and making use of the old components as spares. Often the components used are common across many applications. In the absence of this as a solution, there is still value to be derived from recycling various components and printed circuit boards (PCBs) for the gold and any other precious/rare metals.

2.9 Responsibly sourcing circular-minded suppliers & contractors

2.9.1 Environmental management and internal governance

At Beinn Ghlas, Nadara is committed to the responsible sourcing of circular-minded suppliers and contractors through its continually evolving sustainable supply chain procurement practices by ensuring the decommissioning of energy assets is fully aligned to circularity and helping the supply chain to decarbonise.

Circularity and moving away from a linear economy are an environmental necessity. Scotland's highly skilled and experienced renewable energy sector is well placed to lead the way through developing new industry standards and prioritising the principle of the Waste Hierarchy through resource recovery, reuse, repair and remanufacture.

Any materials and products procured on behalf of Nadara, where practical, should be selected with LCA in mind based on optimal recyclability and reuse content, for example implementing cradle to cradle design principles.

Recycling and reuse targets should be in place and in alignment with Nadara's own company targets, with compulsory reporting to be delivered on request as and when required by Nadara.

For raw materials, packaging and embedded carbon should be minimal, and environmentally benign materials used where possible. The use of recyclates will be encouraged as well as maximising the lifespan of procured products.

2.9.2 Sustainable Management Plans and waste minimisation

A Sustainable Management Plan (formerly referred to as a Waste Management Plan) may be requested of all suppliers and contractors to identify and audit intended material and proposed waste management streams.

All construction waste should be required to be as minimal as possible through the application of the Sustainable Management Plans, and suppliers and contractors will be required to follow the principle of the Waste Hierarchy to ensure resources are managed efficiently by identifying and mitigating against unsustainable practices.

Waste prevention must be prioritised where practical, followed by reuse, recycling, and recovery, with landfill being the last option following an exhaustive review of the Waste Hierarchy process.

2.9.3 Tendering and sustainable procurement practices

A strict tender procurement process for Beinn Ghlas will ask tender submissions to demonstrate clearly how construction environmental management processes can implement circular and green technologies on site designed to improve efficiencies and to reduce and remove any negative construction impacts on the environment.

All suppliers and contractors will be expected to have a Responsible Sourcing Policy, a Sustainable Procurement Policy or similar in place in alignment with current standards.

During the tender stage for the construction phase, prospective suppliers and contractors should demonstrate how they can offer lower-carbon alternatives to conventional construction and transportation methods. They will be asked to demonstrate how they can utilise and support innovative technologies to support circularity in collaboration with Nadara.

2.9.4 Sustainability and health and safety

Nadara will endeavour to ensure that suppliers and contractors make best attempts to put circular and sustainable processes in place, provided that the method statements and risk assessments and the tools and equipment all maintain the highest level of health and safety performance and strictly adhere to health and safety where appropriate.

2.9.5 Sustainability and supplier & contractor reporting

All suppliers and contractors should expect to be able to report on the following environmental sustainability benchmarks when requested during and after the construction phases:

- Annual reporting on Scope 1 & Scope 2 Greenhouse Gas (GHG) emissions in alignment with the UK Governments environmental reporting guidelines
- Reductions in embodied carbon through the procurement of construction materials and assets on behalf of Nadara
- If requested, provide externally validated carbon data by accredited third parties to recognised standards, such as ISO14064 and ISAE3000 [Ref. 17] and [Ref. 18]
- Waste management data in tonnage, including those materials prevented, reused, recycled, recovered, and sent to landfill.

3. Measuring and capturing the benefits of Beinn Ghlas' circular-focused decommissioning

3.1 Overview

The deployment of renewable energy infrastructure is essential to avoid the worst effects of climate change and, according to the International Renewable Energy Agency (IRENA)'s World Energy Transitions Outlook 2024 [Ref. 19], a tripling of installed renewable power capacity is required by 2030 in the pursuit of achieving a climate threshold of 1.5 degree Celsius above pre-industrial levels. This will require a substantial number of materials such as steel, concrete, aluminium and copper, as well as putting significant demands on supply chain capabilities.

A circular approach to renewables is necessary to achieve ultra-low energy generation sources and reduce greenhouse gases through minimising resource use and waste, but it also creates significant socioeconomic opportunities. Decommissioning old wind farm assets and constructing and operating new, repowered wind farms significantly contributes towards achieving net zero targets, but it can also create circular sustainable businesses and jobs and deliver new supply chains.

The economic benefits associated with circular renewables can help to reduce operational costs through delivering improved and more efficient products and services, designed to meet modern circular economy sustainable benchmarks, and will contribute towards local and community social wellbeing through new employment and business opportunities.

Demand for circular economy principles within the supply chain will increase as material demands for building new renewable energy infrastructure projects increase, creating opportunities for circular-focused businesses who can grow and adapt to help create solutions that can enhance the efficiency of material use within the Scottish Wind Energy Sector.

3.2 Beinn Ghlas Wind Farm

The planned Beinn Ghlas decommissioning works and required material solutions thereafter can result in substantial socioeconomic benefits, particularly in geographic locations close to and surrounding wind energy infrastructure, such as in the Argyll and Bute region.

The repowering of Beinn Ghlas presents an exciting opportunity for the local economy and for the businesses and communities surrounding the wind farm as well as the wider Scottish and UK economies. Nadara recognises the importance of early engagement to help facilitate and achieve this level of local economic gains through circularity and decommissioning and is committed to working alongside local stakeholders to maximise the benefits arising from the decommissioning.

Nadara's plan to adopt circular decommissioning strategies at a local level has the potential to create a more resilient and sustainable renewable energy sector. By reducing reliance on critical materials and fostering the growth of new and existing supply chains, Nadara can contribute to a more secure and environmentally friendly energy future for both the communities and business surrounding Beinn Ghlas and beyond.

3.3 Reporting on carbon emission reductions

The environmental impact of decommissioning is a growing area of interest for stakeholders and climate impact projects are increasingly important based on the benchmark LCA method. LCA explores the best options to limit negative climate impact reducing CO_2 emissions and can measure health, ecotoxicity and resource depletion like rare earth elements. Nadara endeavours to commit to measuring carbon production and savings throughout the entire Beinn Ghlas decommissioning works via an informed LCA process.

3.3.1 Stakeholder engagement & circularity

The decommissioning and repowering of Beinn Ghlas represents an ideal opportunity for Nadara to engage with key stakeholders to investigate and implement innovative circular solutions that are carbon negative and climate positive.

Ensuring the potential community wealth building and socioeconomic benefits from onshore wind decommissioning are investigated and implemented is of great importance when planning decommissioning works.

A wide range of stakeholders and their input will be relevant in the context of the circular decommissioning of Beinn Ghlas, aiming to gather important feedback and to provide information on the various opportunities and benefits to the local area, initiating dialogue as early as possible.

Through initiating early dialogue on the sustainable circular decommissioning of Beinn Ghlas, Nadara is seeking to help raise awareness of the potential for additional local and community socioeconomic benefits, which include positive impacts such as supply chain opportunities, employment and positive impacts to local businesses.

Nadara will reach out to a wide range of stakeholders, including local residents, community councils, landowners, environmental groups, businesses and government agencies.

Further consultation engagement will be undertaken to receive valuable feedback and on how Nadara seeks to adopt best practice, as well as to measure and capture the benefits of taking a sustainable circular decommissioning approach to the repowering of Beinn Ghlas, including with:

- Argyll and Bute Council
- Scottish Environmental Protection Agency
- Mid Argyll Chamber of Commerce
- Argyll and Bute Renewables Alliance
- University of Highlands and Islands
- Zero Waste Scotland
- Scottish Renewables
- Renewable UK
- CWIC.

Appendix 2 provides an overview of the opportunities and benefits that could be achieved through sustainable circular wind farm decommissioning with general detail on potential job creation, skills, education and training networks.

3.4 Circular supply chain opportunities

3.4.1 Helping support a diverse & circular local supply chain to provide wind farm decommissioning services

Through working with specialist, circular-focused supply chain companies such as Reblade, Nadara is committed to engaging with small to medium-sized businesses to help maximise and strengthen Scotland's renewable energy supply chains. By engaging at a local community level, it is recognised that the decommissioning and repowering of Beinn Ghlas could have the potential to positively impact the region of Argyll and Bute.

Nadara further recognises that the deployment of renewable energy infrastructure requires a wide array of skills, experience and engineering know-how. Achieving maximum reuse, recirculation and recyclability of wind farm components and materials is a key objective of optimal wind farm repowering. A movement towards securing circular practices is an important consideration when selecting companies to help make the energy transition happen sustainably.

Through decommissioning and repowering projects like that at Beinn Ghlas, hundreds of companies and organisations across Scotland can benefit from the socioeconomic opportunities that a growing decarbonisation pipeline offers.

3.4.2 Circular procurement & local companies

Nadara will take an active role in helping inform existing and potential businesses how it plans to undertake the full Beinn Ghlas scope of works and the supply chain it will need to decommission the site optimally and with a circular approach to the forefront.

With critical decommissioning requirements such as technical staff, transport, craneage, on-site support services, plant supply, materials solutions and ground works, to specialist and technical engineering solutions, Nadara will look to support local organisations who are or are willing to be ready to support the decommissioning and repowering of Beinn Ghlas.

Examples of local businesses that could benefit through the repowering of Beinn Ghlas include businesses already working in the renewable energy sector, as well as those wishing to secure new work because of local supply chain opportunities.

Examples of local supply opportunities include, but are not limited to:

- Craneage
- Consumables
- Groundworks and civil contractors
- Scrap metal (steel and cables)
- Site services (construction design and management (CDM) regulations, cabins)
- Plant supply
- Storage
- Accommodation, catering and fuel services
- Technical engineering services (lifts, CDM, staff)
- Material solutions (oil, blades, concrete).

A series of public consultation events will take place in the communities local to Beinn Ghlas in April 2025, following on from previous engagement days. These events will present further opportunities for local businesses and organisations to meet with the project team personally and to discuss how businesses local to the wind farm could secure a role in the Beinn Ghlas decommissioning project.

The project team attending the public events will include a range of specialist staff available to discuss all aspects of the project, including the attendance of a representative from Reblade who can provide information on the circular supply chain opportunities available to local companies, as well as some guidance on innovating to help the renewable sector deliver more specialist circular supply chain innovations and services.

3.4.3 Supporting circular innovation

It is understood that innovative companies are critical to redefining the processes and services in the future of decommissioning and recycling in the energy sector. Through sourcing a diverse and innovation-led supply chain, Nadara commits to support and encourage the vital role that suppliers make in the journey to achieving circularity and net zero emissions in the context of Beinn Ghlas.

Innovative supply chain companies have an opportunity to decommission energy assets through identifying new sustainable applications and solutions for decommissioned materials and components.

Appendix 3 details information on current circular-focused research and development innovation.

3.4.4 Brown jobs with a green twist

With a focus on measuring both carbon and socioeconomic impacts, Nadara will look to map local service suppliers who provide services during the decommissioning works focusing on elements including but not limited to:

- Business locations within a 10, 30, 50 km radius of the decommissioning boundary for all service providers on site
- Numbers, job roles and postcodes of onsite staff
- Numbers, type and postcodes of material solution providers and roles sustained
- Numbers, type and postcodes of all suppliers related to the decommissioning works
- Map all local service providers in use for the decommissioning works (accommodation, fuel supply etc.).

3.4.5 Measuring additional carbon savings

Through identifying and utilising local supply chains and services where practical, Nadara recognises that there can be a significant reduction in the carbon footprint of a wind farm project. This approach not only promotes a reduced carbon footprint through wind farm decommissioning, repowering and operational activities, it also helps pioneer new sustainable and circular solutions and helping catalyst local economic growth.

A circular economy approach through focusing on the benefits of procuring local supply chains can contribute towards a significant percentage reduction in greenhouse gases compared to securing supply chains located geographically further afield.

Furthermore, hiring a local workforce where possible can also enable local businesses to expand their operations and help further reduce carbon emissions in the future by retaining a local service provision that can be utilised during the operational lives of renewable assets.

Nadara and Reblade will also provide full LCA analysis for the material solutions phase of the decommissioning works and provide direct comparisons to more traditional solutions that have been implemented previously across the industry.

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Appendix 1

Background information on wind turbine components and decommissioning

1. Wind turbine components and inside a wind turbine

a) Wind turbine rotor blades

Wind turbine rotor blades work like an aeroplane wing. When the wind blows, a pocket of low-pressure air forms on the downward side of the blade, and it is this pocket of air that pulls the blade towards it; a force called 'lift'. The lift force is much stronger than the wind's force against the front of the blade and causes the rotor to spin around it. Most turbines have two or three blades.

Wind turbine blades are made from fibre-reinforced composites such as carbon fibre, polyester and glass fibre that allow the blades to bend without breaking. They are shaped like an aircraft wing to help catch the wind.

Older blades are carbon fibre and modern blades are typically made from fibreglass. Fibreglass is made from bundles of glass fibre woven into a cloth which is then dipped into resin. Once hardened the material is remarkably strong and lightweight. It is moulded into the aerofoil shape required for the blade to slide through the air and harness the wind.

Wind turbine blades must operate in remote regions where the environmental and weather conditions can be very harsh which is why the materials need to be tough as well as lightweight and durable. The blades are painted in a specific RAL paint to fit with the usual weather conditions, for example in Scotland where it is often cloudy, and turbines exceeding 150 metres (500 feet) require aviation lighting.

b) Rotor hub

The blades are joined to the rotor hub which controls the angle of blades. The rotor hub turns a slow-spinning shaft.

c) Stall-tip

First generation turbines such as the Bonus B44/600s blades cannot pitch at the hub. A mechanism inside the tip and section preceding it allows the tip to rotate independently of the rest of the blade when spinning at slow speeds.

d) Shaft

The shaft transfers the spinning energy of the rotor to the generator. The shaft is connected to a gearbox that makes another shaft (the output shaft) spin much faster.

e) Gearbox

The gearbox increases the speed of the shaft between the rotor and the generator.

f) Generator

The output shaft is connected to a generator that turns the spinning energy into electricity, using electromagnets. The generator uses the spinning energy of the shaft to generate electricity by making a big coil of wire move inside the magnet, and electricity is carried by cables to a transformer, which is then connected to either the local power network or the national grid.

g) Brake

The brake halts the shaft in an emergency.

h) Controller

The controller is an electronic monitoring system that ensures the turbine faces the optimal wind direction. It checks the position of the wind several times per second then moves the turbine, so it is in the best position to catch the wind. If the wind is too slow the blades will not turn, and if it's too fast the controller shuts down the turbine, making them safe and efficient when serviced regularly.

i) Nacelle

The nacelle (also sometimes known as the 'casing') is the main body of the turbine. Inside the nacelle are the generator, the gearbox and the electronics that control the turbine. Rare earth elements are important parts of a wind turbine's permanent operation and are in the nacelle.

j) Tower

The tower lifts the blades off the ground, supports the rotor and the nacelle and is made of steel sections. The rotor blades are mounted on tall towers as there is less turbulence off the ground. During construction, the steel sections are lifted into place by cranes before being bolted together.

2. Wind farm site infrastructure

a) Transformers

Step-up transformers are used on turbines to increase the voltage and ultimately decrease the power losses that occur when transmitting large amounts of current over long distances with transmission lines. Some transformers are internal to the wind turbine, which is the case at Beinn Ghlas.

b) Substation and control building

Inside the substation, transformers convert high-voltage electricity into lower voltages for delivery to the distribution system. The control building takes in all operational information from the turbines such as wind speeds, power output and any faults reported and is the location from which turbines can be remotely operated.

c) Foundations

The primary function of a wind turbine's foundation is to distribute loads into the soil beneath. Vertical and horizontal forces exerted on the turbine foundation stem from its own weight and the force of the wind, respectively.

d) Cables & trenches

These include the transmission lines between wind turbines, transformers and the substation. All the turbines on a site are connected via trenched medium-voltage cables which also house the earth and optical fibre cables.

e) Wind farm tracks

The wind turbines, substation and site entrances are connected by access tracks formed of stone and gravel.

f) Crane hard standings

Areas of compacted gravel are established around the base of each turbine for use by various machinery such as cranes.

3. Wind farm decommissioning practices

a) The resale market

Nadara prioritises reusing wind turbine components within its existing operational assets whenever possible. Decommissioned components may also be retained for spare parts. While a resale market exists for refurbished wind turbines, offering reliable and efficient technology, Nadara will carefully evaluate the cost-effectiveness and carbon impact of this option, ensuring all reused components are thoroughly tested. Refurbished or remanufactured turbines can be a viable alternative to new models, particularly for smaller wind farms facing constraints such as tip height restrictions, access challenges, or limited grid capacity. Additionally, this market provides valuable spare parts for owners of older turbines facing obsolescence issues.

Warranty guarantees are another consideration. This is especially important when considering the reuse of wind turbine blades. Over time, blades weaken due to the bending stresses they experience when rotating as they operate to generate renewable electricity.

4. Reuse & repurpose

a) Wind turbine blades

Wind turbine blades are mostly made of glass fibre and epoxy resin - a composite - which acts like a plastic superglue giving a very strong resilient material, lasting through all sorts of weather conditions. Very little composite waste in the United Kingdom is recycled now, with most going to landfill or energy-from-waste. This presents a big challenge for such a sustainability-minded industry.

Reblade decommissions turbine blades without the use of landfill by pioneering innovative approaches to blade handling that enable circular end-destinations for blade waste. Reblade recognised early on the needs of the renewable energy industry to responsibly decommission in environmentally friendly ways and an increasingly urgent need to develop scalable non-landfill destinations for blade and nacelle waste within the sector. Reblade’s key objective is to ensure blade materials stay out of landfill.

The reuse and repurposing of wind turbine blades into new structures and products through sustainable methodologies is a viable option assuming the structural properties of the composite are being used effectively.

b) Nacelles

Some wind turbine manufacturers utilise glass fibre for their nacelles which are used to house the main mechanical components of the turbine. As mentioned above, the composites are not easily recycled, and no current commercial options are available. The nacelles present a unique opportunity for easy repurposing into various items due to the inherent shape. Examples include repurposing nacelles into commercial glamping pods or offices, and as outdoor sheltered areas. Composite nacelles will be particularly challenging due to the thickness and overall weight of materials used to support heavy components.

c) Other composites

Other common GFRP and CFRP elements of wind turbines include the hubs, spinner covers and transformer housing. These present unique opportunities to devise the best end solution for the material as the transformer box roofs and walls can easily be refurbished and supplied as spares for other wind farms with compatible infrastructure, although the transformer infrastructure at Beinn Ghlas is located inside the base of the turbine tower.

d) Major components

Adoptions of recirculated parts can be achieved through increasing confidence in the product, raising awareness of the benefits of recirculated parts, establishing a dedicated supply chain and developing up to date legislation.

Research into Nadara's current portfolio in the United Kingdom and Europe for the potential of using spares should be taken forth to understand the benefit of storing and maintaining major components. Outside of Nadara there may be scope to sell refurbished parts to the wider market.

5. Recycling

a) Overview

Wind turbine blades, nacelles and spinner covers are predominantly manufactured from GFRP composites, though some onshore wind turbine blades (typically older first generation) can include CFRP composites. Offshore blades and some larger onshore blades also contain internal structural CFRP spars.

The recycling of GFRP and CFRP composites differs due to their carbon and glass fibre materials, and the resulting fibres from both require processing differently to that of virgin fibres.

Several recycling routes have been demonstrated through research and development, with some commercialisation activities taking place and further research ongoing, as illustrated in Figure 6 recycling waste GFRP materials from other sectors.

To date, the volumes of composite waste from the wind sector alone have not been available in sufficient volumes to support significantly scaled-up recycling routes for wind farm derived waste composites in the United Kingdom. Recycling solutions are being developed collaboratively within the sector, however, in anticipation of an increase in wind farm decommissioning, and there are many ongoing research projects and some beginning to show commercial readiness.

b) Mechanical methods

The initial first stage challenge to recycling is the mechanical breakdown of the blades. This can be challenging and energy intensive due to a very strong and highly resistant design feature called the 'spar cap'. The spar cap is specially engineered to create strength and flexibility. It varies in thickness along the length of the entire blade, from the root, similar in principle to that of a steel girder, providing the strength and flexibility that is required for the blade to safely operate in all weather conditions, whilst absorbing loads from rotational and wind forces.

Figure 6: Recycled GFRP fibres – potential usage

Reference: Photos courtesy of: Princess Yachts, Filon Products, Stormking, Industrial GRP and Creative Composites [Ref 20].

c) Chemical recycling

Turbine blades are hard to recycle. Some research and development companies and academic institutions are trialling the burn-off of the plastic components using strong chemicals to dissolve the resins. What remains is the fibre, which can be used to make new products, but these processes aren't perfect. They all take a great deal of energy, and the recovered fibre is degraded through the very fierce technology required. This means chemical recycling is likely to remain economically challenging for the foreseeable future.

d) Thermal recycling

Pyrolysis is a recycling method used for wind turbine blade disposal. It involves heating the waste at high temperatures without oxygen. This process breaks down the materials into gas, liquid, and solid forms. Components like epoxy resin, thermoplastic polyurethane, carbon fibre, and glass fibre can be broken down effectively. Valuable substances such as phenol and p-isopropenylphenol can be extracted from the liquid products. Pyrolysis also removes the resin while preserving the fibre materials' integrity.

However, the high temperatures can harm the fibre surfaces and lessen their strength. Typical pyrolysis processes for polymers occur between 400 and 700°C, depending on the composite's type. This temperature range breaks down the polymer matrix and retrieves the fibres.

There is no clear data on the LCA of pyrolysis. Reblade expect to find that due to the extreme heat/pressure required that the energy expenditure will far surpass that of other mechanical recycling methods. If the fibres reclaimed from this method are of a higher strength than other processes, then the potential for offsetting the production of new GFRP may make up for this energy usage. More research is required to understand the applications for the reclaimed fibres and the market for them.

e) Cement kilns

As an alternative to landfill and recovery options, trials are seeing smaller quantities of composites taken from wind turbine blades and other components for coprocessing in cement kilns. This is classed as a combination of recycling and recovery in the EU Waste Framework Directive and requires mixing with other materials to keep the calorific value (CV) low and manageable.

The shredding of blades to be incorporated into cement is not yet a palatable option; but in the absence of commercially available circular recycling options, it is a potential route that could be scaled up pending funding and trials, some of which are ongoing in the UK, to achieve an economical route for the processes to become commercially viable. This is something that is proving difficult to achieve currently.

Importantly, incineration in a cement kiln is not considered a recycling route for carbon fibre turbine blades (commonly associated with older first-generation wind turbines) because the carbon fibres would burn like coal. Only glass fibre materials would be applicable should a commercial route become available. It is also important to note the need for established cement kiln material handling processes to ensure materials and chemical contents are consistently achieving strict limits for certain chemicals required to be managed. Halogens are very limited, such as chlorine and bromine where limits are around 0.8% and 0.25% respectively, which rules out glass fibre with high levels of fire retardants.

6. Recovery

a) Energy-from-waste

A significant amount of composite material is diverted from landfill to incineration, burning the organic parts and recovering the energy in a process known generally as energy-from-waste (EfW).

When applying waste hierarchy principles, recovery is favoured over landfill however, and importantly, it should be highlighted that the LCA when undertaken may not recommend this to be the most carbon negative option. This is because burnt fossil fuel releases greenhouse gases, so unless recovery directly replaces a more negative impact, such as directly replacing the combustion of mined fossil fuels, then the LCA for recovery compared against landfill is likely to be more carbon intensive.

Further, the high CV from burning wind turbine blades and other composite components is not ideal because the incinerators are usually limited by the CV of the burnt fuel as opposed to the actual mass of the materials. This is reflected in the fact that EfW plants typically charge a gate fee for the materials based on the tonnage of material committed to EfW recovery and not the actual energy produced.

It is also important to note that not everything is burnt in the process of recovery. Ash containing glass fibres or mineral filler is either sent to landfill or put into aggregate which does not count as recycling in accordance with the Waste Framework Directive.

In summary, wind turbine blades are not recommended for incineration, and reuse, remanufacture and recycling (where practicable, and when technologically and commercially available) are preferable.

7. Disposal

a) Landfill

Landfill should only be the last option following a thorough review of the Waste Hierarchy.

Appendix 2

Decommissioning skills and benefits

1. Circular jobs creation

There are significant opportunities within the renewable energy sector to create long-term sustainable green jobs related to the circular economy, all requiring a diverse range of skills.

These circular roles have already begun to emerge and will increase significantly as whole site decommissioning and repowering projects take place shortly, creating new jobs not necessarily aligned with traditional science, technology, engineering, and mathematics (STEM) subjects.

These will include roles such as industrial designers supporting sustainable and circular manufacturing and taking reused energy assets, specialists applying circular processes and solutions for decommissioned materials, and many more roles specialising in directly and indirectly supporting a sustainable and circular economy.

The table below provides examples of emerging circular roles being created through Scotland's growing decarbonisation pipeline.

Table 1: Examples of new and emerging circular economy job roles

Circular economy job title	New job role in creation?	Personnel sought from other 'traditional' roles, such as...
Clean-Tech Company Directors	Yes	Cross sector - business minded individuals with a central focus on environmental and climate change target driven priorities
Sustainable Development Managers	Yes	Project management, environmental managers, civil, electrical and structural engineering, manufacturing, contract managers
Sustainable Energy Optimisation Engineers	Yes	Blade technicians, composites engineers
Circular Materials Resource Managers	Yes	Those with experience in extraction of raw materials and manufacturing
Research, Development and Innovation Circular Development Managers	Yes	Cross sector (including third) and those with experience in extraction of raw materials (primary), manufacturing (secondary), or service industries
Circular Health, Safety, Environment and Quality Managers	No	Renewables, composites, and construction

Source: Reblade.

The decommissioning and material management of wind farms will create significant job creation opportunities as well as opportunities for business growth through the supply chain. Zero Waste Scotland's estimate of 1.2-1.4 million tonnes of materials from decommissioned wind farms by 2050 underscores the scale of the challenge and the opportunity for Scotland to lead in wind turbine recycling and a circular economy approach [Ref. 21].

With this scale of decommissioning, Scotland has the potential to become a leader in wind turbine component reuse, refurbishment, and recycling to create jobs, stimulate economic growth, and contribute to a more sustainable future.

2. Decommissioning skills & education

Decommissioning job opportunities arising from making the shift from that of a take-make-waste economic model to one that maximises value extracted from resources are significant and supported by the Scottish policy landscape. Keeping goods and materials in a loop is good for the economy, not just the environment, and requires a pipeline of skills and education to support new circular skills and jobs.

Nadara recognises that integrating sustainability and the circular economy with internal skills and training programmes and opportunities supports the promotion of a circular economy mindset within the organisation. This approach will be woven throughout the organisation's development activities to help nurture critical thinking that supports the principles of circularity, enabling employees to make informed decisions to support a more sustainable future.

Nadara also recognises that hundreds of organisations across Scotland are working hard to collaborate, upskill, innovate, expand and develop circular skills to help make the energy transition happen. Nadara is committed to supporting companies spearheading the renewable energy revolution and will look to work with those organisations who are upskilling their workforces and growing capabilities to meet the needs of our future energy system.

3. Decommissioning-focused training networks

Deploying renewable energy infrastructure requires a vast array of skills and the potential job creation and skill demand associated with circularity across the energy supply chain from infrastructure construction to end-of-life and decommissioning is increasingly significant. The economic opportunities created in remanufacturing, reuse and refurbishment is becoming clear as assets reach end-of-life.

Greater awareness of material demands as Scotland continues to develop and construct new energy infrastructure means there is a sustainable, economic and social responsibility to embed circularity creating a demand for specialised engineering skills associated with extraction, remanufacturing and asset management services.

With a focus on decommissioning of wind assets at Beinn Ghlas, there is an opportunity to identify the emerging roles to support decommissioning through reuse, remanufacturing, and refurbishing and to engage with local community wealth building organisations to ensure the opportunities from Beinn Ghlas are realised.

Appendix 3

Supporting circular-focused research & development

1. Wind turbine end-of-life recycling projects

There are multiple areas of research within the recycling of end-of-life wind turbines, with the aim of achieving technology readiness as well as achieving circularity.

In general, these are:

a) Pre-treatment methodologies

These are the pre-recycling processes required before any recycling can take place. They include:

- Handling of blades
- Cutting of blades
- Shredding of blades
- Sorting of the downsized blade materials.

b) Fibre reclamation processes

There are currently two types of fibre reclamation processes that are in various stages of technical and commercial viability:

- Thermal-based such as thermal pyrolysis
- Chemical-based such as chemical solvolysis.

c) Upgrading (or recycling) of recovered fibres

It is still unclear which solutions for blade recycling will prove to be the most practical, and profitable, and research continues to help develop the most circular and sustainable options. Technical, economic, environmental and social criteria will all support decision making when determining the optimal methods in place for recycling in the future to ensure robust and transparent decision making when it comes to determining the best technologies for end-of-life blade recycling systems.

d) Recyclable blades

Original Equipment Manufacturers (OEMs) are inventing dissolvable resins. This separates the resins from the glass fibres so they can be used for new products, such as suitcases and scaffold boards. This technology is cutting edge, but it's at an early stage and much more research is needed.

The barriers to widespread adoption are cost, availability and urgency. The key benefit of recyclable blades is not likely to be realised until end-of-life, 25-30 years in the future, meaning the roll-out of recyclable blades is still many years in the future.

e) Rare earth magnets

It is predicted that by 2040 there will be a significant shortfall of rare earth magnets. This will potentially slow down progress in the transition to net zero. Research and development is already underway to help find new ways of sourcing magnets, as well as looking to establish ways to reduce the associated environmental impacts and obstacles. The sector is committed to pioneering circular supply chain innovation to overcome these challenges and the first wave of large-scale wind farms now planned for decommissioning could present an opportunity to support the recycling of rare earth elements.

f) The recycling of composite materials

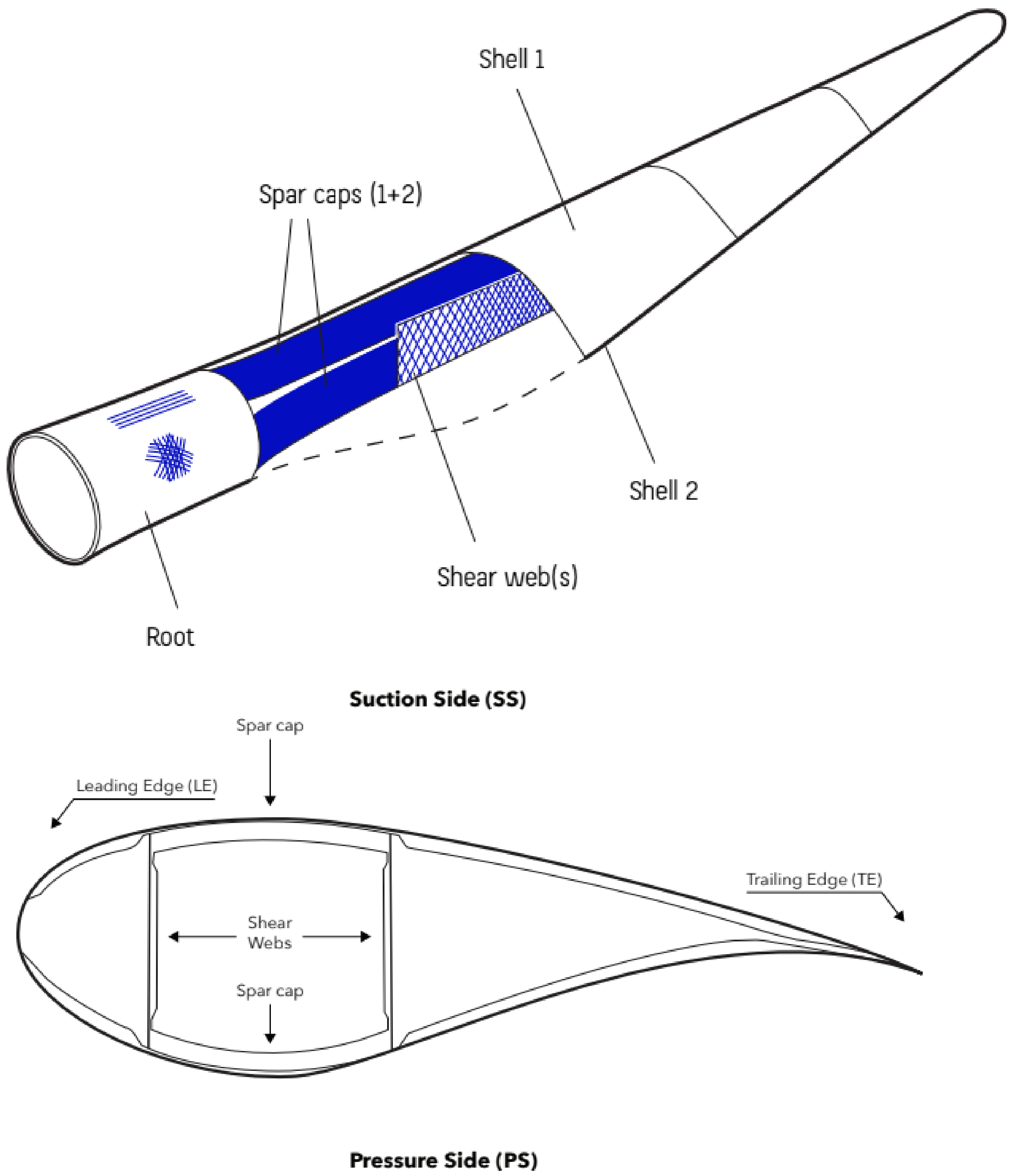
The objective of developing methods for recycling industrial composite materials such as GFRCs and CFRCs, has been in development for some time now through a mix of academic and industrial research and development. The sector is working hard to commercialise practical recycling solutions that can manage wind turbine blades and other composite materials to become feedstock for other second-life innovative products. However, the challenge to finding these processes is that they must fit the market demand in terms of:

- Price competitiveness
- Quality of performance
- Positive carbon balance
- Positive environmental impact.

Mechanical recycling processes suit some composite materials, such as some composite waste from automotive, aviation, electrical and manufacturing sectors where materials can be shredded, milled and then ultimately remoulded into other products or into recycled construction materials. This is also true for some composites within the renewables sector; however, end-of-life wind turbine blades present a particular difficulty. This is down to challenges in achieving the aforementioned criteria due to the inherent design nature of them. The processing of wind turbine blade materials has, and continues to be, trialled using several different recycling processes, but to date these processes are still challenged and the commercialisation yet at scale remains unclear.

To understand why this is the case for wind turbine blades it is necessary to understand a typical commercial wind turbine blade's design and physical morphology.

Figure 7: Wind turbine blade morphology



Reference: (2019) [Ref.22]

Blades are primarily made from glass-reinforced plastic (GRP) sheets bonded via resin, and core material is sandwiched between layers of glass fibre. The spar caps are made from many layers of unidirectional GRP, which essentially act as the girder down the length of the blade and provide most of the strength. As the spar caps are so strong they are also very difficult to break down and shred.

Most commercial GRP recycling processes are fine-tuned to take in specific quantities of material so any contaminants or changes may ruin batches yield quality. This is where blades can cause problems. As the material makeup can vary massively from each blade type or blade generation, this makes building a recycling solution to facilitate all turbine blades very difficult. Reblade observe large variations in the resin used to bind the GRP, with whatever was the cheapest option at the time of manufacture that also fit their specifications being used. First-generation blades were also often over engineered as they wanted to increase safety factors, so carbon fibre is used to strengthen the shell or spar. Core materials can differ as well from high density foam to balsa wood.

A recycling solution that can effectively manage material variation and can be supplemented with various other GRP waste is key for commercial maturity and widespread usage across the industry.

Appendix 4

Glossary of terms

Term	Definition
Circularity	A sustainability concept that aims to reduce waste and pollution by keeping products and materials in use. It's based on the idea that products should be designed with their end-of-life in mind.
Circular job	Circular jobs are jobs in repair, reuse, resource recovery and recycling. These jobs can extend the life of products and close raw material cycles meaning waste products of one process become the raw material for other processes.
Cradle to Cradle	According to the C2C (Cradle to Cradle) approach, compared to conventional recycling, the quality of raw materials used in the production of goods is maintained throughout the multiple lifecycles of products. The production processes, use and reuse of products are designed to maintain the quality level of the raw material over countless lifecycles, thus avoiding the production of waste.
Consumption	The usage or consumption of products and services meeting (domestic) demand. Absolute consumption refers to the total volume of either physical or monetary consumption of Scotland's economy. In this report, when we talk about consumption we are referring to absolute consumption.
Downsizing	Allows for cutting and shredding (only cutting for landfill) and in the case of mechanical recycling, also grinding.
Finite materials	Materials that are non-renewable on timescales relevant to the economy, i.e., not geological timescales. Examples include metals and minerals; fossil forms of carbon such as oil, coal, and natural gas; and sand, rocks, and stones.
Green deal	The European Green Deal represents the new growth strategy presented on 11 December 2019 by the European Commission. This aims to transform the EU into a fair and prosperous society with a modern economy in which growth is decoupled from resource use, competitive and efficient as well as climate neutral by 2050.
Circular skills	Knowledge and abilities needed to work in a circular economy that aim to reduce negative environmental impacts and waste.
Green Deal Investment Plan	The European Green Deal Investment Plan (EGDIP), also referred to as the Sustainable Europe Investment Plan (SEIP), was presented on 14 January 2020 and is a cornerstone of the Green Deal proposed by the Commission. Specifically, this envisages the mobilisation of at least 1,000 billion EUR in sustainable investments over the next decade to achieve the objectives identified by the European Green Deal.
Green economy	A green economy can be defined as an economic system capable of generating improvements in human welfare and social equity, capable of significantly reducing environmental risks and combatting resource scarcity. In simpler words, it can be thought of as a low-carbon, resource-efficient and socially inclusive economy.
Green job	Green jobs are jobs that contribute to the preservation or restoration of the environment or conserve natural resources.
High-value recycling	Refers to the extent to which, through the recycling chain, the distinct characteristics of a material (the polymer, the glass or the paper fibre, for example) are preserved or recovered to maximise their potential to be reused in a circular economy.
Lifecycle assessment (LCA)	LCA is a methodology that can be used to quantify the environmental impact of a product through all or selected stages of its lifecycle.
Lifespan/lifetime	The period from when a product is released for use after manufacture to the moment it becomes obsolete beyond recovery at product level.
Materials	Substances or compounds are used as inputs to production or manufacturing because of their properties. A material can be defined at different stages of its lifecycle: unprocessed (or raw) materials, intermediate materials and finished materials. For example, iron ore is mined and processed into crude iron, which in turn is refined and processed into steel. Each of these can be referred to as materials.
Material footprint	Also referred to as Raw Material Consumption (RMC), it is the attribution of global material extraction to the domestic final demand of a country. In this sense, the material footprint represents the total volume of materials (in raw material equivalents) embodied within the whole supply chain to meet final demand. The total material footprint, as referred to in this report, is the sum of the material footprints for biomass, fossil fuels, metal ores and non-metallic minerals.
Material flows	Represent the amounts of materials in physical weight that are available to an economy. These material flows comprise the extraction of materials within the economy as well as the physical imports and exports (such as the mass of goods imported or exported). Air and water are generally excluded.
Net extraction abroad (NEA)	Represents the difference between the trade balance of products and that of the raw materials needed to produce them. The difference

	between the two represents the 'actual' or net quantity of raw materials that have been extracted abroad to satisfy domestic consumption.
Non-virgin materials	Materials that have been previously used. This includes materials in products that have been reused, refurbished or repaired; components that have been remanufactured; materials that have been recycled. Also referred to as 'secondary materials'.
Reverse logistics	Supply chains dedicated to the reverse flow of products and materials for the purpose of maintenance, repair, reuse, refurbishment, remanufacture, recycling, or regenerating natural systems.
Raw Material Equivalent (RME)	Is a virtual unit that measures how much of a material was extracted from the environment, domestically or abroad, to produce the product for final use. Imports and exports in RME are usually much higher than their corresponding physical weight, especially for finished and semi-finished products. For example, traded goods are converted into their RME to obtain a more comprehensive picture of the 'material footprints'; the amounts of raw materials required to provide the respective traded goods.
Raw Material Consumption (RMC)	Represents the final domestic use of products in terms of RME. RMC, referred to in this report as the 'material footprint', captures the total amount of raw materials required to produce the goods used by the economy. In other words, the material extraction necessary to enable the final use of products.
Recycling	The process of breaking down waste materials and reforming them into new products and materials.
Refurbishment	This is when a component is completely broken down into it constituent parts, inspected, with broken or worn parts replaced and then reassembled and repainted. Refurbished parts should all come with a warranty that is as good as their new equivalent.
Remanufacture	Remanufacture is the most comprehensive of the circular economy with each component being broken down and inspected, approved, repaired, or replaced. Each remanufactured component will come with a lifespan that is as good as its equivalent in new as well as the same warranty period.
Repair	The restoration of a product or material.
Resources	Includes, for example, land, water, air and materials. They are seen as parts of the natural world that can be used for economic activities that produce goods and services. Material resources are biomass (like crops for food, energy and bio-based materials, as well as wood for energy and industrial uses), fossil fuels (coal, gas and oil for energy), metals (such as iron, aluminium and copper used in construction and electronics manufacturing) and non-metallic minerals (used for construction, notably sand, gravel and limestone).
Resource recovery	This entails the collection of waste materials.
Reuse	The use of materials multiple times without significantly breaking down or transforming the base materials.
Reverse logistics	Type of supply chain management that moves goods from customers back to the sellers or manufacturers.
Sharing economy	Refers to an economic system that is more efficient in the use of resources and characterised by a different management not only of physical goods (e.g. means of transport, clothes, accessories), but also of digital products, space, skills, ideas and money. The structure of the sharing economy also places a strong emphasis on the importance of social relations in economic life.
Secondary materials	Materials that have already been used and recycled. This refers to the amount of the outflow which can be recovered to be re-used or refined to re-enter the production stream. One aim of dematerialisation is to increase the number of secondary materials used in production and consumption to create a more circular economy.
Sector	Any collective of economic actors involved in creating, delivering and capturing value for consumers, tied to their respective economic activity.
Socioeconomic cycling	The technical term for the Circularity Metric. It comprises all types of recycled and downcycled end-of-life waste, which is fed back into production as secondary materials. Recycled waste from material processing and manufacturing (such as recycled steel scrap from autobody manufacturing, for example) is considered an internal industry flow and is not counted as a secondary material. In the underlying model of the physical economy used in this report, secondary materials originate from discarded material stocks only. The outflows from the dissipative use of materials and combusted materials (energy use) can, by definition, not be recycled. Biological materials that are returned to the environment (for example, through spreading on land) as opposed to recirculated in technical cycles (for example, recycled wood) are not included as part of socioeconomic cycling. Energy recovery (electricity, district heat) from the incineration of fossil or biomass waste is also not considered to be socioeconomic cycling, as it does not generate secondary materials.
Socioeconomic metabolism	Describes how societies metabolise energy and materials to remain operational. Just as our bodies undergo complex chemical reactions

	to keep our cells healthy and functioning, a nation (or the globe) undergoes a similar process—energy and material flows are metabolised to express functions that serve humans and the reproduction of structures. Socioeconomic metabolism focuses on the biophysical processes that allow for the production and consumption of goods and services that serve humanity: namely, what and how goods are produced (and for which reason), and by whom they are consumed.
Sustainable Development Goals	The 2030 Agenda for Sustainable Development adopted by all United Nation Member states in 2015, provides a shared blueprint for peace and prosperity people and the planet, now and in the future including, of the 17 Sustainable Development Goals, number 12: Responsible Consumption and Production.
Territorial-based carbon footprint	Is based on the traditional accounting method for GHG emissions, with a focus on domestic emissions, mainly coming from final energy consumption. A consumption-based carbon footprint uses input–output modelling to not only account for domestic emissions but also consider those that occur along the supply chain of consumption (for example, accounting for the embodied carbon of imported products).
Total material consumption	Is calculated by adding RMC (material footprint) and secondary material consumption (cycled materials).

Sources: CWIC/Reblade