END OF LIFE MATERIALS MAPPING FOR OFFSHORE WIND IN SCOTLAND

REPORT FROM PHASE 1 OF THE ELMWIND PROJECT

JULY 2022

In partnership with:

Project Information

The End of Life Materials Mapping for Offshore Wind in Scotland is the report from Phase 1 of the ELMWind project and is part of the Circular Economy for the Wind Sector Joint Industry Programme (CEWS JIP).

The CEWS JIP brings together major offshore wind stakeholders to find solutions to various sustainability challenges posed to the industry. The JIP conducts research on offshore wind materials treatment options at end of life, asset operations decision near end of life, and decommissioning offshore wind assets. The aim is to stimulate innovation and support the supply chain to develop solutions.

More information and to register interest can be found at https://ore.catapult.org.uk/stories/cews/

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CONTENTS

01

SUMMARY

When Scotland's first offshore wind farm was commissioned in 2010, it would have been hard to believe that offshore wind would become the 'backbone' of the energy sector, leading the way in the green energy transition.

Today, offshore wind has become crucial in meeting the Scottish Government's target of Net Zero emissions of all greenhouse gases by 2045, committed in the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 [1], and with interim targets to cut emissions by 75% by 2030, and 90% by 2040 from the 1990 baseline.

It is repeatedly reported that renewable electricity generation was equivalent to 97% of Scotland's gross electricity consumption (total electricity generation minus net exports) in 2020 [2]. However, there is a long way to go to decarbonise other sectors. In 2020, the energy demands of the heat sector accounted for 51.5% of Scotland's total energy consumption, followed by transport at 24.5% and electricity demand at 21% [2]. The Scottish Government has set a target to generate 50% of Scotland's total energy consumption from renewable sources by 2030 [3].

Scotland has nearly 2 GW of offshore wind capacity already operational and another 3.65 GW consented, with 2 GW of this currently under construction [2]. The industry is demonstrating great confidence in Scotland's offshore wind sector as significant developments are progressing without the full support of Contracts for Difference (CfD) [4]. The drive to achieve 11 GW of offshore wind capacity in Scotland by 2030 and 75 GW across UK waters by 2050 has created an unrelenting drive to develop high-performance, next-generation wind turbines that will achieve the necessary energy capture and cost efficiency [5] [6] [7]. Such a significant increase in energy infrastructure requires an equally daunting need for millions of tonnes of materials to manufacture the necessary components and structures. The UK's industries currently depend on substantial imports of raw materials and components manufactured from all over the world [8] [9].

Following COP26, there is no time like the present for wind and other industries to pause and take stock. Pooling our collective experience and resources, we can achieve the feats of engineering that will make the energy transition and pan-sector circular economy a reality. This report is the first phase in our work to identify, study and determine potential material flows within a circular economy, to reduce waste, retain material value and generate economic opportunities with significant positive environmental impacts. The challenge of finding good solutions for decommissioning and reusing these materials in the coming decades is already becoming an urgent challenge for the onshore wind sector as the first generation of wind farms come to the end of their service life [10].

It is often stated in academic literature that 85-90% of a turbine is technically recyclable [11]; however, no large-scale wind farm decommissioning has put that theory to the test in the UK. To fully satisfy the sector's future growth plans and sustainability goals, finding the right solution for reducing waste, refurbishing components and recycling materials is imperative.

By 2050, it is currently estimated that between 161 and 492 turbines could be decommissioned in Scotland and this is expected to generate approximately 1.5 - 2.4 million tonnes of materials. Steel is the largest contributor to decommissioning and is also in highest demand to meet future requirements, with approximately 14.7 million tonnes needed to meet the 2050 turbine build out targets. Additionally, up to 8.4 million tonnes of concrete, 1.5 million tonnes of ductile iron casting, 0.26 million tonnes of glass and carbon fibre, 93 thousand tonnes of neodymium and 67 thousand tonnes of copper will be required to build the wind farms of the future.

POOLING OUR COLLECTIVE EXPERIENCE AND RESOURCES, WE CAN ACHIEVE THE FEATS OF ENGINEERING THAT WILL MAKE THE ENERGY TRANSITION AND PAN-SECTOR CIRCULAR ECONOMY A REALITY.

Due to the magnitude of materials involved, recycling is of key importance, not just with material requirements, but in reduction of carbon emissions. Analysis shows that steel (including foundations) represents up to 90% of the total mass of a wind turbine and contributes up to 70% to the total greenhouse gas emissions (GHGE). The potential carbon saving by using recycled steel combined with small contributions of copper and cast-iron, is estimated to offer up to 34% reduction in GHGE.

This report sets out the huge opportunity for the supply chain in designing solutions to tackle the circular economy challenge and capture a global market that encompasses the decommissioning of up to 85 GW of offshore wind capacity (cumulatively and assuming a 25-year lifecycle) by 2050, in addition to 1,200 GW of onshore wind [12]. Moving turbines towards zero waste provides significant opportunities for the supply chain through refurbishment and life extension, remanufacturing, reuse, repowering and upgrading of components, before we even begin to consider recycling raw materials. If realised, the University of Leeds estimates that a circular economy from offshore wind in the UK could extend the current UK Government projection of 60,000 jobs within the sector by 2030 [13] by an additional 5,000 jobs in areas of life extension and remanufacturing alone, and up to 20,000 jobs within a full circular economy supply chain [14]. However, this number could also increase following a recent industry review that almost doubles the UK Government prediction up to 100,000 jobs in offshore wind by 2030 [15] [16].

As you will find in these pages, there are many reasons for optimism in the many techniques and technologies that are already being trialled in this area. Collaboration between the wind and other sectors will be crucial to accelerating circular economy technologies and supply chains. It is an exciting prospect to take this forward with industry partners and show how the wind turbine, the workhorse of the clean energy revolution, will take its next steps towards circularity.

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02

INTRODUCTION

Zero Waste Scotland commissioned the Offshore Renewable Energy (ORE) Catapult to conduct a review of the offshore wind industry in Scotland, quantifying the expected profile of decommissioning and planned future developments from the present (2022) to 2050.

The project identifies circular economy challenges and opportunities, based on the estimate of the material volumes generated from decommissioning activity, and material requirements for future installations. By initiating early discussions across the industry and its supply chain, it increases the potential for these materials to be retained domestically and reused, to enable cost-effective and sustainable development of the Scottish offshore wind market.

The Scottish Government recognised in Scotland's Circular Economy Strategy [17] that the energy infrastructure sector holds significant opportunities in the move towards a circular economy. Offshore wind currently accounts for approximately 11% of Scotland's renewable power generation capacity [2]; however, the Scottish Government has set an ambition to substantially grow its presence in Scottish waters and increase capacity to 11 GW of energy installed by 2030 [3], equating to around 1,000 large, fixed turbines. The ScotWind leasing round awards announced in January 2022, surpassed all expectations with almost 25 GW of additional capacity set to be installed over the next decade [18].

Additionally, the Innovation and Targeted Oil and Gas (INTOG) leasing process was announced in March 2022. The aim of this initiative is to have smaller, more focused offshore wind developments for the decarbonisation of oil and gas assets in the North Sea. This latest round could add a further 4.5 GW of offshore wind capacity [19]. If all the currently proposed projects in the pipeline (including ScotWind and INTOG) were to be successfully granted planning consent, Scotland's offshore wind capacity would reach almost 40 GW by 2033 [19].

Offshore wind turbines have a typical design life of 25 years and new analysis from ORE Catapult has identified that on this basis, approximately 600 offshore wind turbines in UK waters are due to be decommissioned by 2030 [20]. However, precise data on the make-up of offshore wind turbines and their components is often commercially sensitive and there is currently no breakdown of how the decommissioning timeline translates into material quantities. Furthermore, offshore wind decommissioning has only been undertaken in a handful of instances globally, including one site in the UK (Blyth, two turbines in 2019) and there is limited information on the recycling, reuse, refurbishment or disposal strategies employed during decommissioning.

In the limited instances where onshore wind decommissioning has occurred in Scotland, most of the turbine has been sent for disposal via scrap metal aggregation for reprocessing overseas, or UK landfill [21]. However, a report by Zero Waste Scotland [10] has demonstrated that significant circular economy opportunities exist through the reuse, refurbishment and repurposing of both components and materials from onshore wind farms, and this could also generate significant revenue for owners/operators. It is likely that similar potential exists for offshore wind turbines.

Capacity-building to serve both the onshore and offshore wind decommissioning market is strategically important for Scotland, as this will become a UK-wide (and indeed global) activity in the decades to come. Data obtained by this study could enable strategic decisions to be taken on inward investment in Scotland, by both the public and private sectors.

The aim of this project is to quantify the profile of offshore wind decommissioning in Scotland, from the present day to 2050, the material volumes generated through this activity and the resource demand to fulfil the future pipeline of projects. Put simply, the project aims to answer the questions, what materials do we have, where can they go, (as shown in Figure 2-1) and where are they needed, to support supply chain growth and stimulate commercial investment in circular economy solutions.

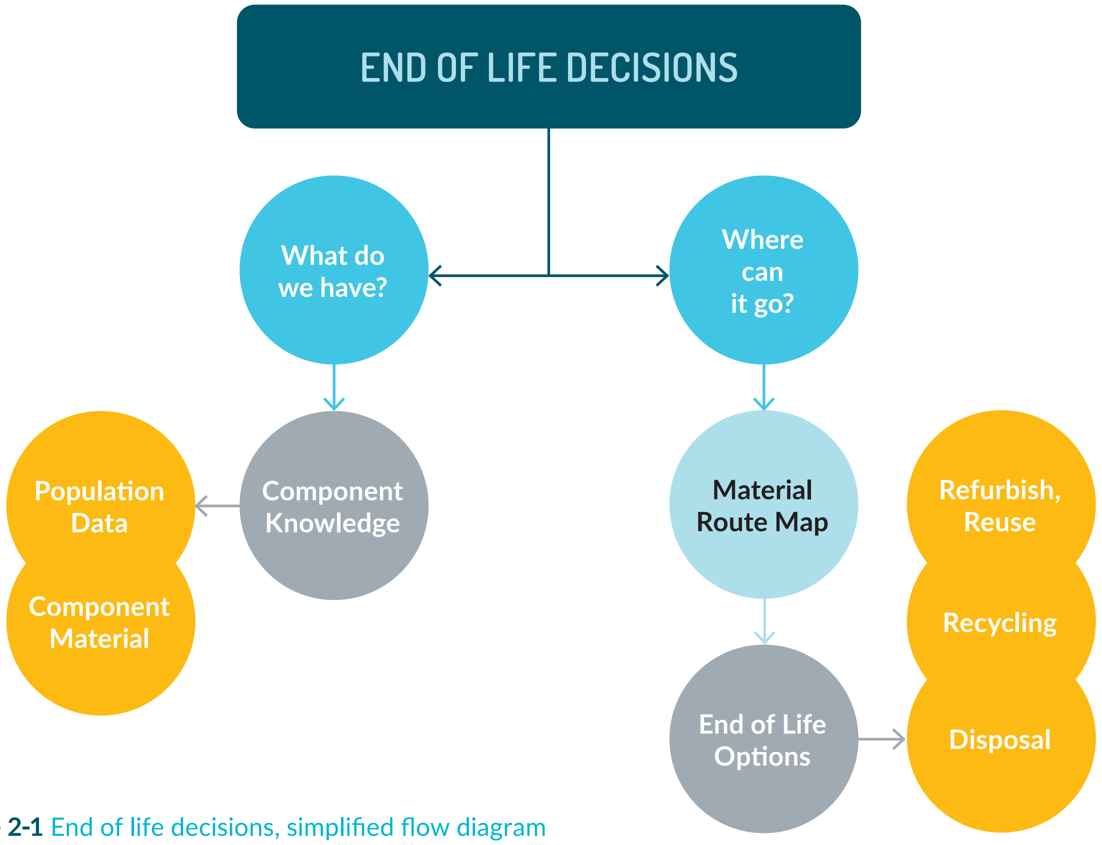


Figure 2-1 End of life decisions, simplified flow diagram

03

OFFSHORE WIND IN SCOTLAND

3.1
CURRENT INSTALLED CAPACITY

There are currently six operational offshore wind farms in Scottish waters since 2021 and another three expected by the end of 2022, which will give a total installed capacity of about 3.5 GW, alongside ORE Catapult's 7 MW Levenmouth offshore demonstration wind turbine in Fife. The operational wind farms in Scotland listed in Table 1, show that Moray East is the largest single installation (950 MW) and it is also the largest single source of renewable energy in Scotland. An additional two offshore wind farms (Seagreen and Neart na Gaoithe) are due to be fully operational in Scotland by the end of 2022 and have also been included in Table 1.

Table 1 Scotland's operational offshore wind farms

Wind farm name	Developer	Foundation type	Operational	No. of turbines	Installed capacity (MW)
Robin Rigg	RWE Renewables	Fixed	2007	58	174
Hywind Scotland	Equinor	Floating	2017	5	30
Aberdeen	Vattenfall	Fixed	2018	11	93
Beatrice	SSE/Red Rock Power	Fixed	2019	84	588
Kincardine – phase 1	Cobra/Pilot Offshore	Floating	2018	1	2
Kincardine – phase 2	Cobra/Pilot Offshore	Floating	2021	5	48
Moray East	Ocean Winds	Fixed	2022	100	950
Seagreen	SSE Renewables/TotalEnergies	Fixed	2022*	114	1,180
Neart na Gaoithe	EDF/ESB	Fixed	2022*	54	448
Total				**432**	**3,513**

* Under construction, expected year of commissioning

A further six sites are also expected to be operational in the next few years, with approximately 6.6 GW currently under construction or in development. All the projects listed in Table 2 have already received full consent, except Berwick Bank which is still in the concept development stage. This wind farm alone will provide up to 4.1 GW of offshore wind capacity in Scotland. An additional 25 GW has been leased in January 2022 under the ScotWind leasing round and another 4.5 GW is expected to be announced before the end of 2022 under INTOG. ScotWind and INTOG will be covered in more detail in section 6.

Table 2 Wind farms with authorised consent

Wind farm name	Developer	Foundation type	Operational	No. of turbines	Installed capacity (MW)
Forthwind Phase 1	Cierco	Fixed	2024	1	12
Inch Cape	Red Rock Power	Fixed	2026	72	1,080
Pentland	Copenhagen Infrastructure Partners	Floating	2025	8	100
Moray West	Ocean Winds/Ignitis Grupe	Fixed	2024	60	850
Seagreen 1A	SSE Renewables/TotalEnergies	Fixed	2026	36	420
Berwick Bank	SSE Renewables	Fixed	2029	307	4,150
Total				**484**	**6,612**

3.2
PLANNED GROWTH

Scotland has set a target of generating 50% of the country's total energy consumption from renewables by 2030 [3]. Offshore wind proves to be a significant resource to meet those targets, with approximately 25% of Europe's entire offshore wind potential passing though Scottish waters, highlighting the large scale of green energy investment opportunities [22].

The official Scottish Government target is to achieve 11 GW of installed offshore wind capacity by 2030 [3]. With over 4 GW currently installed and consented, there is a great deal of ambition and drive to exceed that target [19]. The recent ScotWind leasing announcement included 17 winning projects (shown in Figure 3-2) with the potential to generate up to 25 GW of offshore wind energy, where floating wind is expected to play a significant role [18]. The projects are expected to secure at least £1 billion in supply chain investment for every 1 GW of capacity proposed. They will also generate around £700 million in revenue for the Scottish Government and represent the world's first commercial scale opportunity for floating offshore wind [18].

An announcement on INTOG proposals is also anticipated before the end of 2022 [19]. These are expected to develop up to another 4 GW of offshore wind capacity, to provide renewable energy to power and support decarbonisation of existing, operational fossil fuel assets. A further 500 MW is due to be auctioned in a separate 'pot' of sub-100 MW developments, that will be linked to areas focussed on other areas of decarbonisation, such as green hydrogen production [23]. INTOG is the first leasing process of its kind and will be managed in a similar manner to ScotWind by Crown Estate Scotland.

As shallow water sites fill up, developers are looking to deeper waters and sites further from shore for future projects. Beyond 60m water depth the cost of fixed-bottom foundations becomes prohibitive. Floating turbines are undergoing significant Research and Development (R&D) to capture this huge potential market, with large-scale projects expected from 2030. With 15 GW of floating wind projects leased under ScotWind, ORE Catapult assumes a rapid build out to meet the 2030 target, followed by a steady rate of growth as more projects are expected under INTOG (Figure 3-1). Scotland could reach 11 GW of installed offshore wind capacity, assuming this includes at least 5.2 GW of ScotWind's projects. Globally, it is estimated that installed capacity will reach 220 GW by 2030, with major markets establishing around the North Sea (UK, Germany, Netherlands) and China [20]. Floating wind is a particularly attractive technology type for

Scotland, whose waters are some of the deepest in the UK and it can be utilised to access areas of high and consistent wind speeds.

Offshore wind turbine size has increased rapidly and continues to do so, with turbine capacity increasing from 1.5 MW models in 2005, to the world's largest 14 MW demonstrator built in 2021 [24]. To date, each successive GW of installed capacity requires fewer turbines to be installed. It has been confirmed that 12 MW turbines will be used for the Dogger Bank projects in England from 2025 [25] and it is anticipated that 15 MW turbines will be the standard globally by 2030. Development does not look like it will stop there, with potential for further developments and increases beyond this to 18 or even 20 MW by 2035 [26] [27].

UK OFFSHORE WIND CAPACITY FORECAST

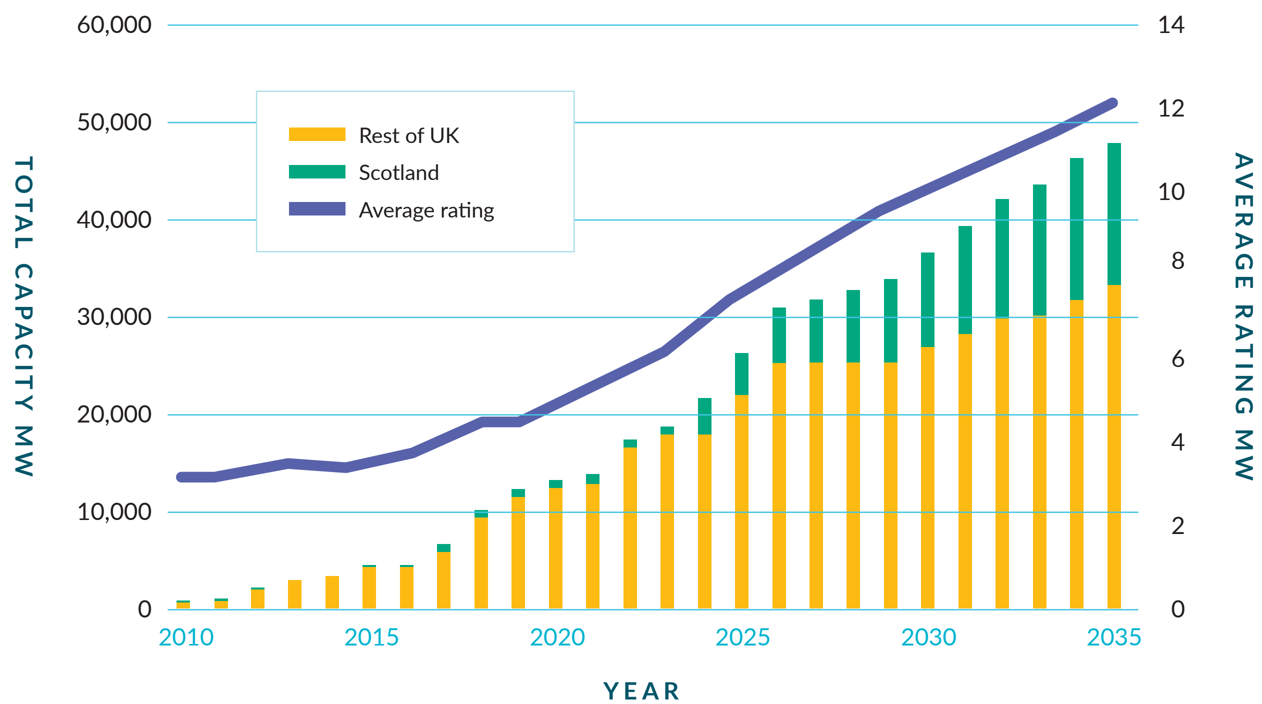
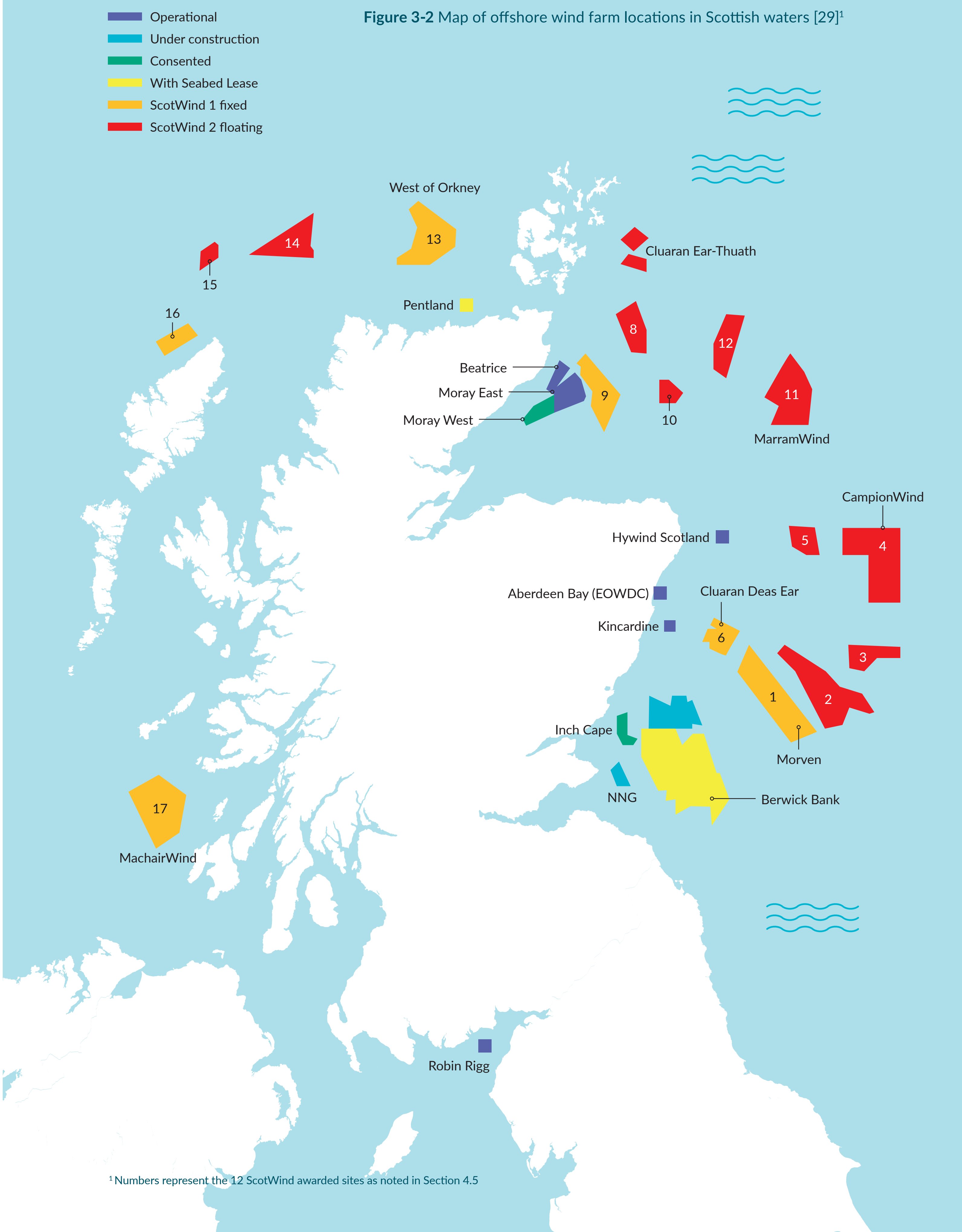


Figure 3-1 UK offshore wind capacity growth forecast

The increase in offshore wind capacity and offshore wind farms will also lead to an increase in supporting infrastructure regarding substations, array cables, export cables and a higher demand for installation and O&M vessels. In April 2022, the UK Prime Minister, Boris Johnson, presented a plan to boost Britain's energy security. This included an increased target of up to 50 GW of operating offshore wind capacity by 2030 [28]. While this is an impressive target with great ambition, projects will need to be consented and CfDs awarded before the true opportunity and impact on growth and accelerated timelines for projects under development can be properly evaluated. Therefore, the UK projections in this section rely on the analysis of the current offshore wind consented and leased, and do not include targets based on the most recent Government ambitions.

Figure 3-2 Map of offshore wind farm locations in Scottish waters [29][1]



[1] Numbers represent the 12 ScotWind awarded sites as noted in Section 4.5

3.3
DECOMMISSIONING EXPECTATIONS

The End of Life Material mapping for the Wind sector (ELMWind) project objective is to unlock opportunities for a reduction in end of life environmental impact and cost for the offshore wind industry. By deploying a systematic framework to analyse and capture the material makeup of the industry and current state-of-the-art recycling, in addition to reuse and refurbishment strategies, an understanding of how the industry currently foresees the end of life material handling will help to identify challenges and opportunities for the recycling, reuse and refurbishment of components. ORE Catapult working in collaboration with key stakeholders, such as Zero Waste Scotland, aim to develop a component database and materials route map for end-of-life of wind industry assets.

A programme of stakeholder engagement is being conducted as part of this study. This stakeholder engagement will continue beyond the completion of this report to stimulate the conversation and provide a catalyst for identifying gaps and opportunities in the current supply chain and strategy. At the time of writing over 40 organisations have been engaged and detailed discussions have been held with 25 companies from across the industry, including operators, Original Equipment Manufacturers (OEMs), supply chain, academia and government institutions.

Much of the focus for decommissioning policies has been towards meeting the international obligations developed primarily from The United Nations Convention on the Law of the Sea (UNCLOS), IMO and the OSPAR convention [30]. These are focussed on the marine environment and returning the seabed to its previous condition once all structures and installations are removed. Once the material is returned to shore, the EU Waste Framework Directive has directed the establishment of waste and environmental legislation which governs waste management policy. Depending on the waste and how it should be handled determines whether the Environmental Protection Act 1990 or the Waste Management Licensing (Scotland) Regulations 2011 is most applicable for waste management licencing [30].

The following sections provide a summary of the key discussion points from the stakeholder engagement. However, large-scale offshore wind decommissioning projects are not expected to happen for another 10 to 15 years. Therefore, there are few if any absolute certainties and everything is still open for debate, with major decisions yet to be made. There is a keen interest from across the board on how decommissioning can be managed in a sustainable and circular manner, retaining resources and developing more local supply chains.

> CURRENT EXPECTATIONS FROM WIND FARM OPERATORS CONCLUDE THAT A PERIOD OF LIFE EXTENSION FOR OPERATIONAL WIND FARMS, BEYOND THEIR ORIGINAL DESIGN LIFE, IS LIKELY.

3.3.1 Operators

Current expectations from wind farm operators conclude that a period of life extension for operational wind farms, beyond their original design life, is likely. This will most probably be followed by partial or full repowering of the site, replacing old, smaller capacity wind turbines with new, significantly larger capacity machines. This is already happening onshore with applications for repowering existing sites in Scotland being submitted for consent in 2022. This means that there is an element of uncertainty for when offshore wind turbines will be fully decommissioned and materials returned to shore for refurbishment, reuse and recycling. This continues to be a moving target with improvements in operational understanding, maintenance and remote monitoring tools. The initial design life for these systems is 25 years and life extension is expected to stretch to a further 5-10 years, provided the necessary consent agreements allow and spare parts are available for maintenance.

When it comes to decommissioning, operators generally do not intend to become involved in the details of the process. They do not want to become decommissioning organisations themselves and will therefore rely on the expertise of contractors to responsibly manage what happens to all the materials returned to shore. However, some companies are pressing for more environmental solutions, asking decommissioning companies during the tendering process for contracts to provide at least two alternative options to landfill, for the recycling and / or reuse of the materials at the end of life. The intention is that this will encourage the market to find alternative solutions and persuade other organisations to consider the environmental impacts of their operations and processes.

There is a clear trend of wind farm operators seriously considering the environmental impacts and implications of decommissioning and not just seeking the most cost-effective means to an end. Vattenfall has set a target to achieve a 50% recycling rate of wind turbine blades by 2025, and 100% by 2030, by self-enforcing a landfill ban on end of life blades from their wind farms [31]. Ørsted has announced its decommissioning commitment to reuse, recycle, or recover all wind turbine blades from all wind farms globally as part of their company strategy, working towards achieving a carbon neutral footprint by 2040 [32].

3.3.2 Original Equipment Manufacturers

It has been suggested that one solution to end of life management would be for OEMs to reclaim their equipment and do their own refurbishment, reuse and recycling inhouse. While this appears to be a reasonable suggestion from the discussions held, the practicalities mean that OEMs are not keen to reclaim the responsibility and liability from the operators. A significant reason for this is the explosive expansion in planned offshore wind developments, meaning that the order books are full for years, if not decades to come. Their focus is on completing the new orders for next generation wind turbines and continued R&D towards bigger and more efficient machines.

From discussions, the expectation for a refurbished, second-hand or "grey parts" market will most likely be claimed, established and coordinated by third parties in a circular economy supply chain, either working alongside or fully independent of the OEMs. One potential path forward that could be considered by OEMs is for them to share the original design and manufacturing information for postproduction components, to support the development of a life-extension, circular economy, third sector. This would provide a significant step towards R&D of new refurbishment and recycling technologies and processes.

3.3.3 Contractors

New businesses are beginning to establish themselves in the maintenance, refurbishment and repair markets where a gap has appeared, when turbine models are out of manufacture and spare parts are difficult, if not impossible to source. Some of these companies are featured in case studies in section 11. However, there remains a serious question as to what will happen to these components when the wind farms are decommissioned and the second-hand market need for these parts shrinks or disappears. While reuse and refurbishing are fantastic first steps in the waste hierarchy (Figure 3-3), the materials will eventually need to be recycled.

Due to current expectations for life extension and the potential that onshore wind farms will be repowered with turbine models that are smaller than the largest offshore turbines, one option for decommissioning offshore wind turbines could be to reuse the whole system as part of a repowering programme of onshore wind farm sites. However, information sharing would be critical to the success of any second-hand turbine market to enable the continued operation of assets. This has been raised as a serious challenge for the resale of turbines to developing countries that may not have the same access to materials, tools and resources as the countries exporting them.

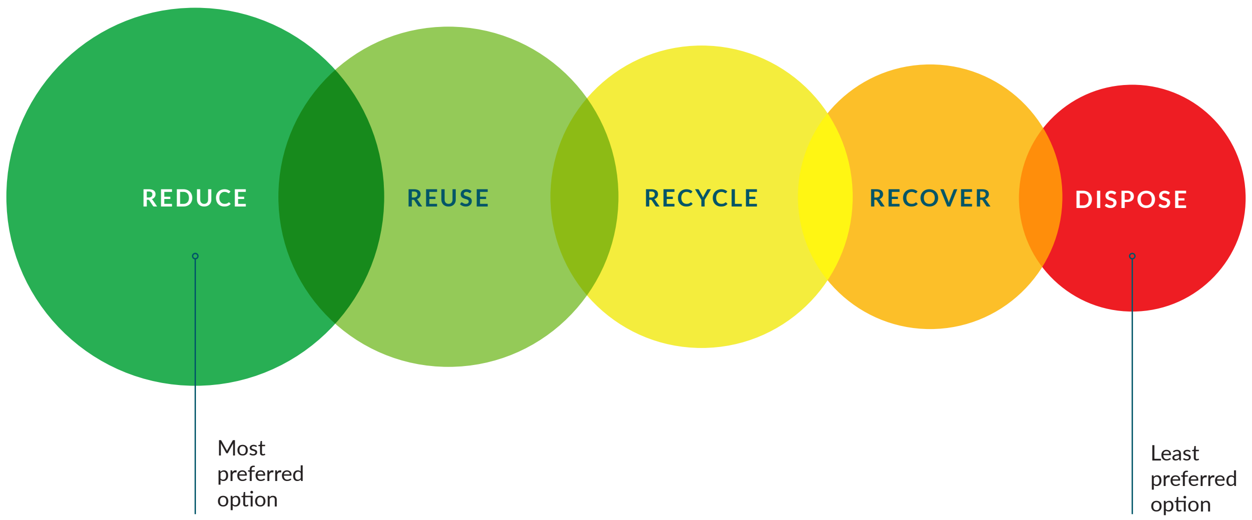


Figure 3-3 Waste hierarchy

04 RESOURCES IN OFFSHORE WIND

4.1 TAXONOMY

Wind farm and turbine components, as well as their constituent materials, currently have no standardised definition across the industry with respect to recyclability, reuse, refurbishment, or disposal.

To ensure that this project is effective for industry, supply chain and other stakeholders, a common Terms of Reference (ToR) is required. This analysis used a combination of ORE Catapult's breakdown of wind farm development stages, an in-house Life-Cycle Assessment (LCA) model and insights from past projects to create a representative taxonomy for offshore wind and estimate the mass of end of life materials.

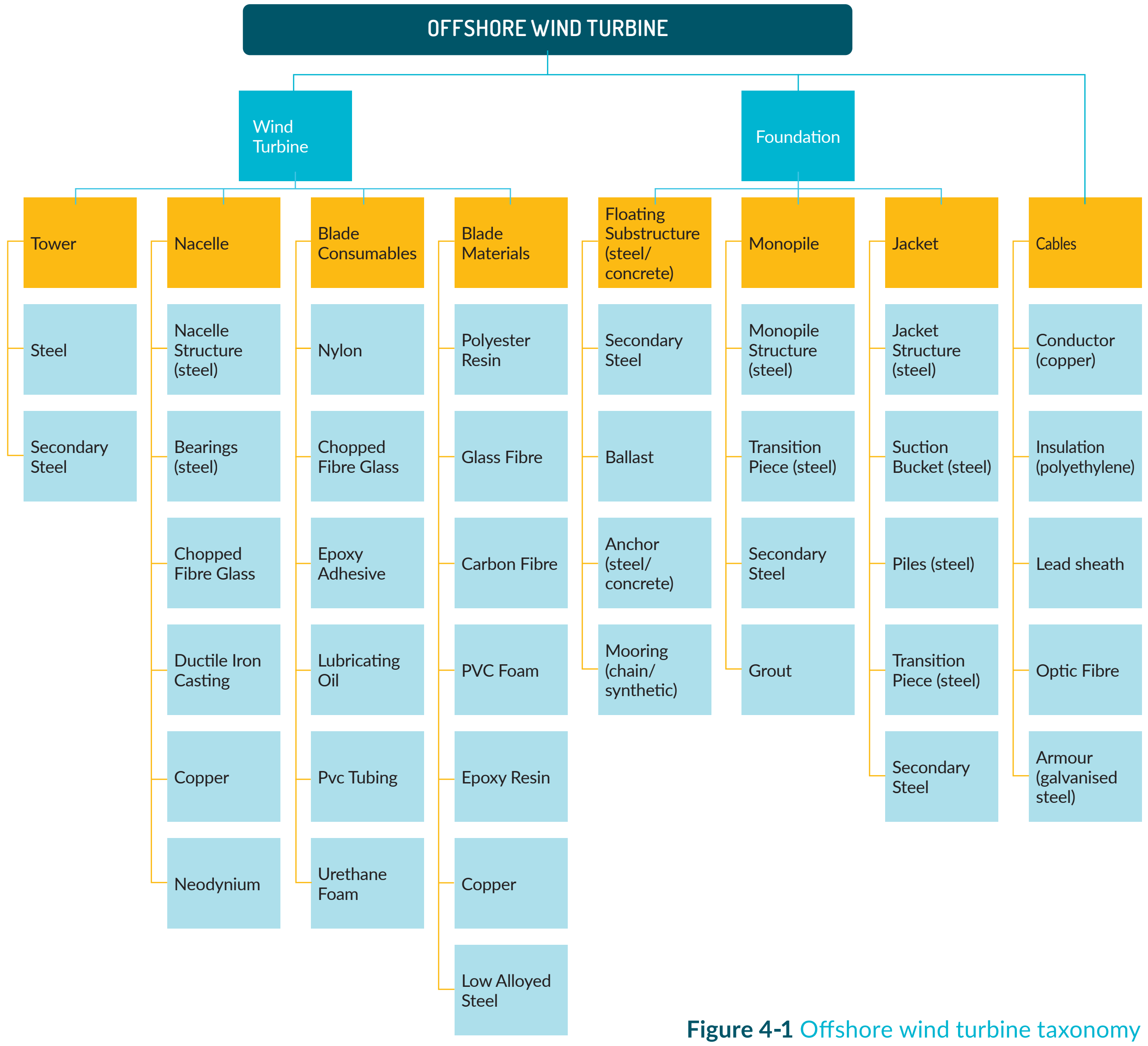


Figure 4-1 Offshore wind turbine taxonomy

4.2
DECOMMISSIONING TIMELINE

The observed and planned rapid growth of offshore wind energy raises the issue of what will happen once these assets reach their end of operational life. Until recently, industry attention had primarily been on cost reduction of offshore wind and decommissioning had not been viewed as a high priority for the sector. The first-generation offshore wind turbines were installed with a planned lifetime of 20 years, which after improvements in design and operations and maintenance (O&M), increased to over 25 years for later turbines. From the latest ORE Catapult estimations, over 3.8 GW of offshore wind capacity in the UK is expected to reach the end of its operational life by 2035 [20]. Newer wind turbine designs are manufactured for longer lifetime (currently the average expected operational life of a wind farm is estimated to be around 27 years, based on ORE Catapult internal analysis), but it is expected that this could reach 31 years for projects installed in 2035. This assumption is based on the decommissioning projections below, where the current design lifespan is assumed at around 27 years, with design improvements leading to an average increase of at least four months per year, without considering life extension or repowering strategies. The estimated number of units ready for decommissioning will be 5,400 by 2066 for the UK and 1,340 for Scotland. This assumes an increase of lifetime to 31 years by 2035 due to design and O&M improvements.

SCOTLAND'S OFFSHORE WIND DECOMMISSIONING TIMELINE

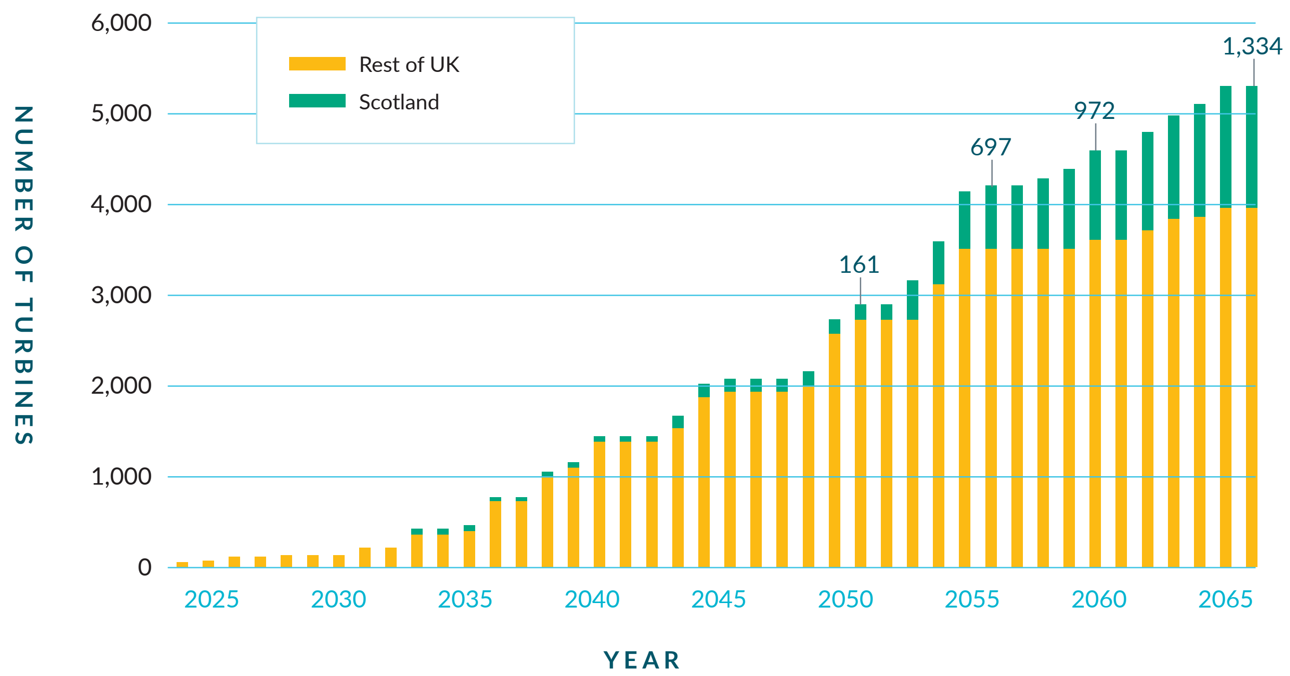


Figure 4-2 Decommissioning timeline of Scotland's offshore wind turbines

Decommissioning is the last phase of a wind farm project lifecycle and is where the developer removes all assets and fulfils their decommissioning obligations as outlined under the Energy Act 2004 [33]. It typically follows a reverse installation process where developers are required to remove all the wind farm parts and restore the seabed to its prior condition. It could be considered sufficient to remove the structures above the seabed, leaving the subsea cables in-situ rather than disturbing the seabed to remove them all. Depending on what will be required, there are significant cost and operational implications associated with logistical spend complications and tough seabed conditions.

> DECOMMISSIONING IS PART OF AN INITIAL LEASING AGREEMENT, WHERE DEVELOPERS AGREE ON A BOND LODGED WITH THE GOVERNMENT AT THE TIME THE LEASING ROUND TOOK PLACE.

Decommissioning is part of an initial leasing agreement, where developers agree on a bond lodged with the government at the time the leasing round took place. This generates a form of security providing that the cash is held in an account intended only for decommissioning, where deductions cannot be made without prior agreement with the Secretary of State [34]. However, this cost can become unrealistic after 25 years or more of asset life. Currently there is no standard legislation in the UK that specifies the best practice after a wind farm operational life ends, therefore decommissioning is currently considered as the default option rather than reuse or life extension. However, the oil and gas (O&G) sector already faces these higher anticipated costs with platform decommissioning [35]. Early consideration of the details and policy level discussions to define a framework of best practice is important in selecting the best strategy for each case.

4.3
GEOGRAPHIC SPREAD

Currently all operational and fully consented wind farms in Scotland are along the east coast. With 12 of the 17 new wind farms awarded in the ScotWind leasing round concentrated along the east coast of the country (Figure 3-2), there is a significant opportunity for its existing ports to support the build out, installation and O&M of Scotland's future green energy infrastructure. The west coast poses a little more of a logistical challenge, due to harsher environmental conditions, smaller existing infrastructure and being further from large centres of population and transport links. However, there is considerable potential for valuable investment in new, custom-designed and built infrastructure, that is not in competition for access from other sectors, to establish centres of expertise in the delivery and O&M of offshore wind.

Many ports and harbours have already begun to investigate and upgrade their facilities to support and facilitate the growth of the offshore wind industry. New quaysides, reinforced harbour walls and dredging to create deeper water access are just a few of the plans already proposed or under construction. Other considerations include on or near site recycling and manufacturing facilities, large areas for lay down and build out, and major O&M bases for continued servicing and operations centres.

05

END OF LIFE MATERIALS – WHAT DO WE HAVE?

To quantify the relevant and necessary materials, a database has been created that records all available data on current offshore wind farms in Scotland, along with a set of formulas that have been developed utilising ORE Catapult's knowledge of current offshore wind farms to date.

This has also enabled the database to generate approximate assumptions for wind farms with limited or sensitive data. Therefore, some assumptions have been made where necessary, including the use of scaling formulas to estimate the mass of materials for each turbine model installed and estimations for the size of wind turbines eligible for installation in the identified future offshore wind sites.

5.1 CURRENT INSTALLED CAPACITY

The key assumptions made in the analysis include:

All the announced ScotWind fixed wind turbines will be commissioned by 2027, and floating wind will likely be by 2031 due to the ongoing development of floating wind substructures and technologies.

Which substructure would be used was based on the assumptions made in the DeepWind presentation slides [36].

Any wind farm which lacked available design life information was assumed to follow a similar lifetime as others which are either commissioned or expected to be commissioned at similar periods.

Any wind farm site which did not specify the fixed foundation typology was assumed to be a monopile structure if situated in a water depth <60m.

Any future floating wind farm which did not specify the typology in use was assumed to be a semisubmersible.

5.2 UNCERTAINTIES

In addition to the assumptions made, there are areas of uncertainty due to a current lack of experience for large scale deployment of floating wind and the still increasing ambition for bigger turbines. Key areas of uncertainty include:

Scaling of wind turbine parts has been based on a single market model meaning other turbines may vary marginally in material. This could have a greater effect once scaling is also introduced. All values shown in tables have been rounded to the nearest 10 tonnes.

Jacket and monopile masses are accurate to a degree but will always vary slightly due to the differences in the ocean environment and seabed conditions.

Export cables have been ignored in this study because it is dependent on each exact instalment location.

The fixed wind site data available will give a water depth range for each area. The monopile and jacket calculations have assumed the higher water depth value available meaning some of the steel outputs for the earlier fixed wind (before 2030) will give a conservative output.

5.3
FOUNDATION TYPES

There are many different offshore wind turbine foundation designs. Fixed bottom structures are nominally categorised by one of the five main designs shown in Figure 5-1.

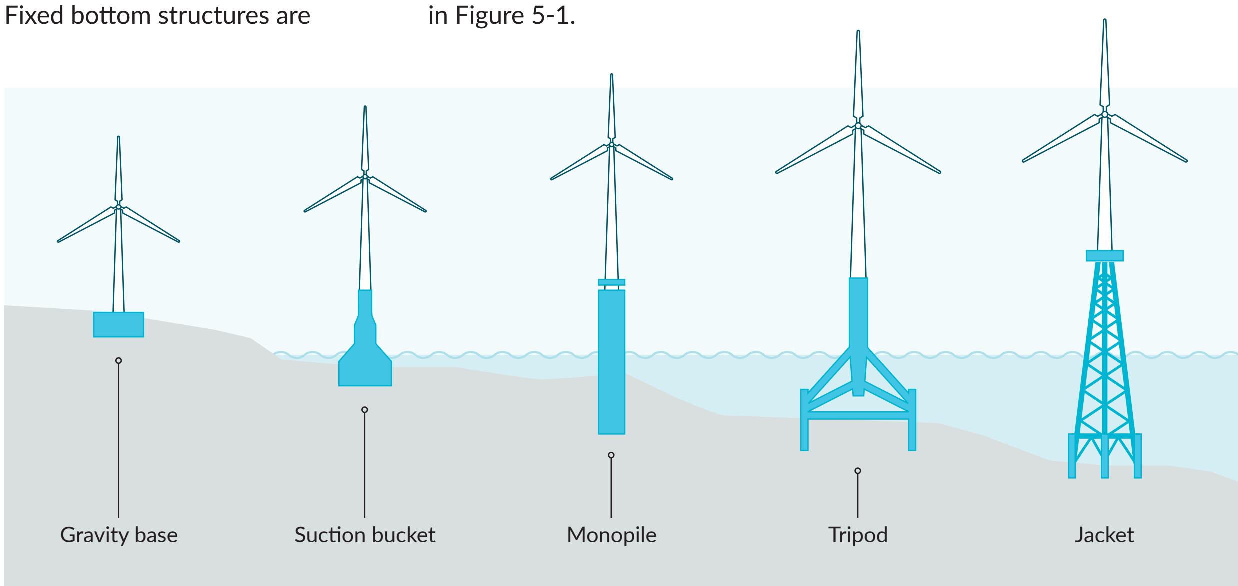


Figure 5-1 Different types of fixed-bottom offshore wind foundations [37]

The common designs related to floating foundations are shown in Figure 5-2. The semisubmersible designs can vary substantially in looks but they are categorised by the fact they gain their stability through a large waterplane area. The material mass related to a semisubmersible, or a barge is expected to be similar which is why in this study the estimated masses for each foundation are assumed to be the same.

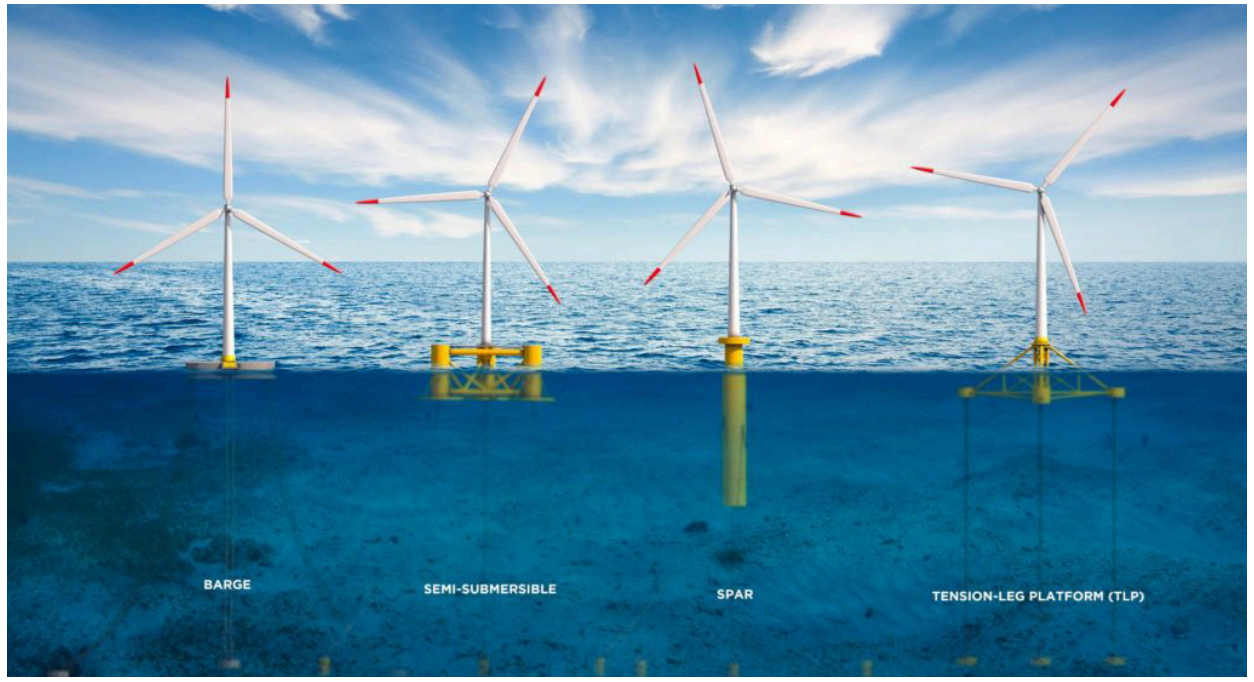


Figure 5-2 Different types of floating offshore wind foundations [38]

5.3.1 Fixed-bottom

The current offshore wind resources in Scotland expected by the end of 2022 consist of nine wind farms and one demonstrator project which have all been established through the Scotland (1, 2, 3) leasing rounds. There are six fixed-bottom wind farms with one using a monopile substructure and the others supported using different types of jacket designs. As stated in section 3.1, a further five fixed-bottom wind farms are expected to be constructed, with three being monopile and two using jacket structures. The largest is the Berwick Bank wind farm which has an expected capacity of 4.15 GW and will be supported using jacket structures that will be secured via piles into the seabed.

Table 3 Fixed-bottom foundation types by offshore wind farm

Wind farm	Commissioning date	No. of turbines	Capacity (MW)	Foundation type
Robin Rigg	15/09/2010	58	174	Monopile
Seagreen	31/12/2022	114	1,180	Jacket (Suction Bucket)
Neart na Gaoithe	31/08/2022	54	448	Jacket (Piled)
Beatrice	31/05/2019	84	588	Jacket (Piled)
Moray East	01/10/2022	100	950	Jacket (Piled)
Aberdeen (EOWDC)	25/07/2018	11	93	Jacket (Suction Bucket)
Forthwind Phase 1	01/09/2024	1	12	Monopile
Inch Cape	15/01/2026	72	1,080	Monopile
Moray West	01/12/2024	60	850	Monopile
Seagreen 1A	01/01/2026	36	420	Jacket (Piled)
Berwick Bank	31/12/2029	307	4,150	Jacket (Piled)

The mass of steel estimated in each jacket and monopile structure (shown in Table 4) were calculated using ORE Catapult formulas which have been created based on industry knowledge of current operational structures. The turbine size and site depth are both inputs for the formula, which contribute to the assessment of the corresponding steel masses used in the construction. The secondary steel and transition piece values were also based on industry knowledge and scaled up for larger designs and deeper waters. Similarly, the jacket foundations use either suction buckets or pin piles to anchor them to the seabed, both are included in the calculations and have been scaled up to suit the equivalent turbine size and depth for each site.

Over 1.97 million tonnes (Mt) is expected to be utilised by all the currently consented wind farms in Scotland, this equates to an average 190 tonnes of steel per MW of capacity.

Table 4 Estimated steel masses of fixed-bottom foundations

Wind farm	Foundation type	Foundation Steel Mass (t)	Suction Bucket Mass (t)	Pin Pile Mass (t)	Transition Piece Mass (t)	Secondary Steel mas (t)	Total Foundation Steel Mass/MW
Robin Rigg	Monopile	26,760	0	0	12,760	3,480	247
Seagreen	Jacket (Suction Bucket)	154,090	19,380	0	28,230	8,660	178
Neart na Gaoithe	Jacket (Piled)	59,060	0	25,350	10,870	3,800	221
Beatrice	Jacket (Piled)	71,370	0	25,890	13,630	5,910	199
Moray East	Jacket (Piled)	93,680	0	40,050	22,340	7,320	172
Aberdeen (EOWDC)	Jacket (Suction Bucket)	5,500	1,760	0	2,180	770	110
Forthwind Phase 1	Jacket (Piled)	320	0	140	250	80	66
Inch Cape	Monopile	240,430	0	0	28,800	4,540	253
Moray West	Monopile	187,950	0	0	24,000	3,780	251
Seagreen 1A	Jacket (Piled)	44,180	0	19,570	9,990	3,020	183
Berwick Bank	Jacket (Piled)	448,120	0	203,750	85,470	25,790	184
Total		**1,331,460**	**21,140**	**314,750**	**238,520**	**67,150**	**198**
Total Steel		**1,973,020**					

Limitations involved in the jacket and monopile calculations relate to the unique environmental conditions of a specific site and the year it is commissioned. Harsher environments may require more material to provide greater strength to withstand the environment while the date of commissioning also plays a factor as designs were typically over engineered in the early stages of offshore wind developments, meaning that additional steel and other materials were used which may no longer be deemed necessary in more modern designs.

Any wind farm which is listed as a jacket foundation but has not been specified further if it used suction buckets or piles, have been assumed to use piles, as they have been utilised more in Scotland compared to suction buckets for fixed wind farms.

5.3.2 Floating

Scotland's floating wind projects (detailed in Table 5) included in (1,2,3) leasing rounds were Hywind, which used a steel SPAR substructure, and Kincardine phases 1 and 2. Kincardine Phase 1 deployed an individual 2 MW demonstrator turbine on a steel semi-submersible, generating confidence for Phase 2 which consists of five 9.5 MW turbines.

Table 5 Floating wind substructure type by offshore wind farm

Wind farm	Commissioning date	No. of turbines	Capacity (MW)	Foundation type
Kincardine - phase 1	24/10/2018	1	2	Steel Semi-Sub
Kincardine - phase 2	31/08/2021	5	48	Steel Semi-Sub
Hywind	01/10/2017	5	30	Steel Spar
Pentland	01/06/2025	8	100	Steel Semi-Sub

Floating wind is still in its early stages of development although Scotland has two of the first commercial floating wind farms commissioned globally. Due to this small number of wind farms, it means there is a lack of data on substructure size and mass. This data is also likely to be commercially sensitive and not shared publicly until it has been operational for several years. This creates difficulties when trying to establish an accurate account of each substructure design. From further industry work and improved communications with developers, ORE Catapult has attempted to make more accurate predictions for larger floating structures and scale downwards for the smaller, earlier designs developed. These estimates are shown in Table 6 below and show that over 54 kilo tonnes (kt) of steel is expected to be utilised in all of Scotland's currently consented floating wind farms with an average of 410 tonnes of steel per MW of capacity.

Table 6 Estimated material masses of floating wind substructures

Wind farm	Foundation type	Substructure mass (t)	Secondary Steel mass (t)	Total Foundation Steel Mass/MW
Kincardine - phase 1	Steel Semi-Sub	1,300	75	688
Kincardine - phase 2	Steel Semi-Sub	13,750	550	301
Hywind	Steel Spar	11,500	475	399
Pentland	Steel Semi-Sub	25,600	980	266
Total		**52,150**	**2,080**	**302**
Total Steel		**54,230**		

5.4 WIND TURBINES

Table 7 shows the breakdown of all Scottish offshore wind turbines by component and material mass. For this analysis, ORE Catapult used data from the Levenmouth Demonstration Turbine in addition to publicly available sources, proprietary knowledge gained from working with clients on validation testing and industry experience, to scale upwards and downwards for a, currently theoretical, 15MW wind turbine. The total material mass from the currently installed offshore wind farms, excluding foundations, is estimated to be up to 1.3 million tonnes with steel being the largest contributor.

Table 7 Estimated breakdown of materials for Scotland's installed offshore wind turbines

Wind turbine component	Material	Total Production (t): Scotland (1,2,3)	Total Turbine (t) Mass/MW
Tower	Total Tower Steel Mass	673,050	66
Nacelle	Total Nacelle Steel Mass	211,180	21
	Chopped Fibre Glass	6,360	0.6
	Ductile Iron Casting	225,500	22
	Copper	5,070	0.5
	Neodymium	13,620	1.3
Blade Consumables	Nylon	550	0.05
	Chopped Fibre Glass	29	0.003
	Epoxy Adhesive	280	0.03
	Lubricating Oil	81	0.01
	PVC Tubing	820	0.08
	Urethane Foam	30	0.003
Blade Materials	Polyester Resin	1,630	0.2
	Glass Fibre	80,420	8
	Carbon Fibre	22,250	2.2
	PVC Foam	8,120	0.8
	Epoxy Resin	34,850	3
	Copper	220	0.02
	Low Alloyed Steel	900	0.09
Total		**1,284,970**	**127**

5.5
SCOTLAND (1,2,3) MATERIAL SUMMARY

A summary of all the materials calculated to be required to deliver Scotland (1, 2, 3) leasing rounds is provided in Figure 5-3. The right axis provides a larger scale for the dominating steel and iron materials.

Assuming a 25 year operational life for all the Scotland (1, 2, 3) leasing rounds, all but Berwick Bank (which has announced an operational life expectancy of 50 years (Berwick Bank Windfarm Offshore Scoping Report) [39] and Inch Cape (which is not due to be fully operational until after 2025), could be decommissioned by 2050 (4C Offshore) [40].

The 1.5 – 2.4 million tonnes of material that could be decommissioned by 2050 will depend on what level of life extension wind farms will go through, particularly the most recently constructed windfarms and those still under construction as part of these leasing rounds.

SCOTLAND (1,2,3) MATERIAL QUANTITIES (KT)

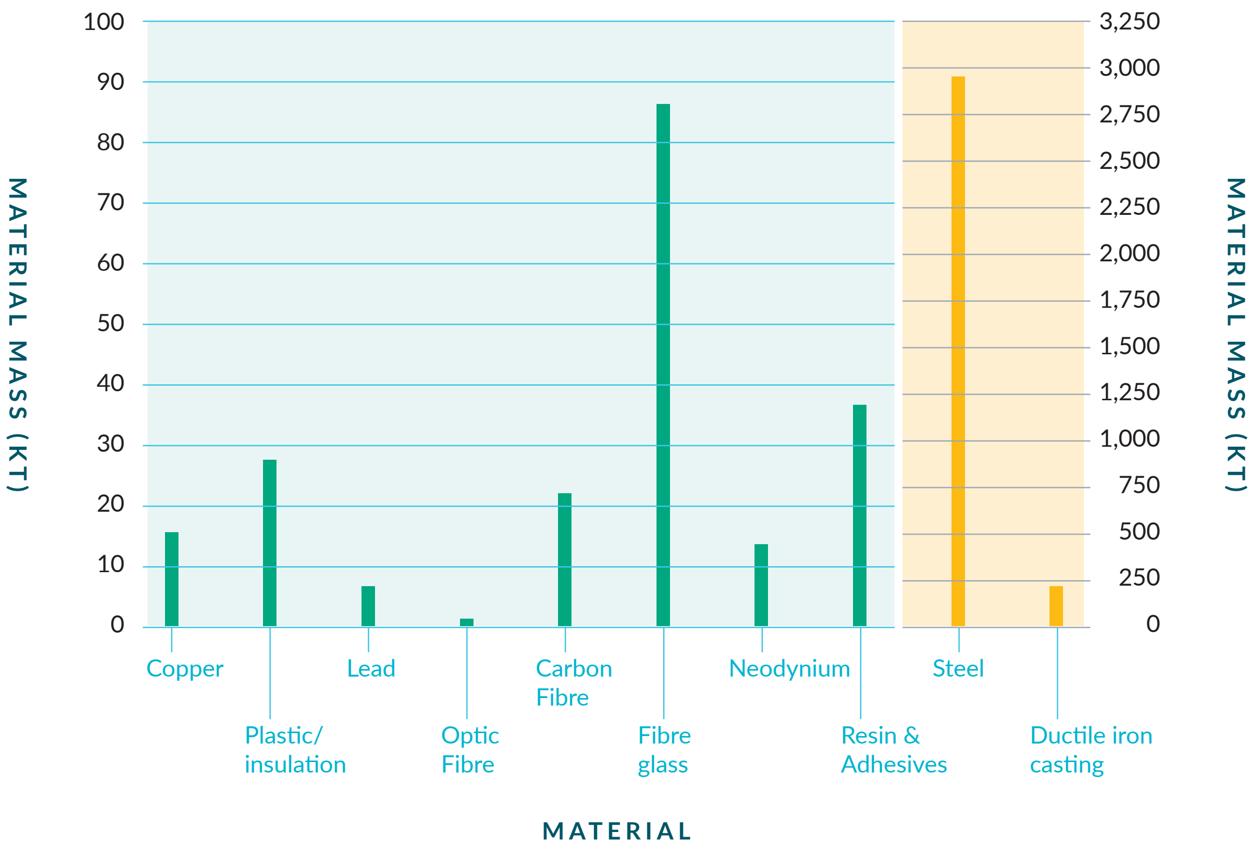


Figure 5-3 Summary of total Scotland (1,2,3) material quantities

06

FUTURE DEVELOPMENTS – WHAT DO WE NEED?

This study initially began as a question of how to decommission offshore wind farms in the most sustainable way possible. However, it evolved over the course of discussions, as it became clear that decommissioning is both a challenge and a significant opportunity for the domestic and global supply chain to help meet the future growth demands of one of Scotland's fastest growing sectors [41].

6.1
SCOTWIND

ScotWind is unlikely to have completed installation of any of its wind farms until the later 2020's or early 2030's and will not be decommissioned until the 2060's at the earliest. However, it is important to understand the material requirements that come with the construction of these wind farms. ScotWind achieved a much higher overall capacity than expected which signalled a much higher material demand. From the results, we have gained an understanding of which companies own which sites and whether the site will host fixed or floating wind but, with regards to specific substructure type, turbine size and mooring configuration – assumptions need to be made.

Using ORE Catapult's industry experience we have made respectable assumptions on which type of foundation will be used for each site based on the owner companies' recent history or interests. It is assumed that fixed wind will be completed earlier than the floating sites, due to the UK having a starting point in the fixed industry already. having a starting point in the fixed industry. Assumptions made regarding turbine size were impacted by this. We expect that by the time the floating farms are manufactured, the industry will be dominated by 20 MW turbines, whereas fixed wind sites will range from 15 MW to 20 MW. The smaller sites are assumed to be constructed quicker, meaning they have been assumed to be lower than the highest turbine output available. The predictions made in the DeepWind Western Isles briefing have also been used to align with the assumptions made in this report [42]. The expected lifetime of these wind farms is set at 30 years, but this will likely increase due to life extension plans, or the fact they have been over-engineered. It is currently difficult to accurately predict how much additional time the wind farms could last, due to the lack of available examples at this size. The expected time frame for installation of these wind farms is known but the exact year may vary. Therefore, a specific year must be used to act as an input into the calculations, and these were selected as 2027 for fixed wind and 2031 for floating.

The mass assumptions made for fixed follow the same assumptions previously stated in section 5.4 but for larger wind turbines. The floating foundation masses which will be used are significantly larger than what is currently in the water meaning assumptions must be made again. ORE Catapult can make appropriate assumptions due to their experience working with substructure developers to create respectable ranges for the different substructures which will be used for ScotWind sites. The turbine assumptions also use the same bases as stated previously in section 5.4.

6.1.1 Fixed-bottom

The fixed-bottom wind farms announced under ScotWind are expected to be commissioned by 2027. The estimated design, capacity and steel masses are detailed in Table 8 and show that over 1.97 Mt is expected to be required to meet the build requirements for ScotWind's fixed-bottom wind farms with an average of 206 tonnes of steel per MW of capacity.

Table 8 Estimated material masses of fixed-bottom foundations for ScotWind projects

Wind farm	Foundation type	Capacity (MW)	Foundation Steel Mass (t)	Pin Pile Mass (t)	Transition Piece Mass (t)	Secondary Steel mas (t)	Total Foundation Steel Mass/MW
Morven	Monopile	2,907	332,740	165,320	44,450	13,160	191
DEME E3	Jacket	1,008	234,190	0	23,800	3,640	260
Caledonia	Monopile	1,000	221,000	0	22,500	3,250	247
West of Orkney Wind farm	Monopile	2,000	442,000	0	45,000	6,500	247
Northland Power-N4	Jacket	840	68,440	37,730	12,560	3,780	146
MaChair Wind	Jacket	2,000	162,960	89,830	29,900	9,000	146
Total		**9,755**	**1,461,330**	**292,880**	**178,210**	**39,330**	**202**
Total Steel			**1,971,750**				

6.1.2 Floating

The floating wind farms announced under ScotWind are expected to be commissioned by 2031. The estimated design, capacity and steel masses are detailed in Table 9 and show that over 2.3 Mt of steel is expected to be required to meet the build requirements for ScotWind's steel floating wind designs with an average of 180 tonnes of steel per MW of capacity.

Table 9 Estimated material masses of steel floating wind substructures for ScotWind projects

Wind farm	Foundation type	Capacity (MW)	Substructure mass (t)	Secondary Steel mass (t)	Total Foundation Steel Mass/MW
SSE Renewables E1	Steel Semi-Sub	2,907	535,050	20,480	191
CampionWind	Steel Semi-Sub	2,610	410,000	15,000	163
Vattenfall-Fred. Olsen-E2	Steel Semi-Sub	2,000	163,590	5,930	85
Cluaran Ear-Thuath	Steel Semi-Sub	1,008	206,640	7,910	213
Marramwind	Steel Semi-Sub	3,000	615,000	22,500	213
Northland Power-N2	Steel Semi-Sub	1,500	307,500	11,250	213
Total		**13,025**	**2,237,780**	**83,070**	**178**
Total Steel			**2,320,850**		

Whereas the estimated design, capacity and concrete masses detailed in Table 10 show that up to 31 kt of steel and 3.37 Mt of concrete is expected to be required to meet the build requirements for ScotWind's concrete floating wind designs with an average of 818 tonnes of concrete per MW of capacity.

Table 10 Estimated material mass of concrete floating wind substructures for ScotWind projects

Wind farm	Foundation type	Capacity (MW)	Substructure mass (t)	Secondary Steel mass (t)	Total Concrete Mass/MW
BlueFloat-Falck Renewables-E1	Concrete Semi-Sub	1,200	972,000	9,000	818
Ørsted-Falck-BlueFloat-NE3	Concrete Semi-Sub	1,000	810,000	7,500	818
BlueFloat-Falck Renewables-NE6	Concrete Semi-Sub	500	405,000	3,750	818
Floating Energy Alliance	Concrete Barge	960	777,600	7,200	818
Maagnora-N3-Floating	Concrete Semi-Sub	495	400,950	4,370	819
Total		**4,155**	**3,365,550**	**31,820**	**818**

6.2
WIND TURBINE

Following a similar methodology as in Section 5.4, the estimate of wind turbine materials for future projects relies on industry knowledge and testing experience. This enabled the use of existing data and scale up estimates where required for ScotWind's offshore wind pipeline, building a more representative view of material masses (Table 11). The total material mass required to complete all wind turbines for ScotWind wind farms, excluding foundations, is estimated to be nearly 4 Mt with steel being the largest contributor.

Table 11 Estimated breakdown of materials for ScotWind 's offshore wind turbines

Wind turbine component	Material	Total Production (t): ScotWind	Total Material Mass/ MW
Tower	Total Tower Steel Mass	1,868,770	75
Nacelle	Total Nacelle Steel Mass	743,140	30
	Chopped Fibre Glass	22,360	0.9
	Ductile Iron Casting	793,520	32
	Copper	17,850	0.7
	Neodymium	47,930	2
Blade Consumables	Nylon	1,740	0.07
	Chopped Fibre Glass	93	0.004
	Epoxy Adhesive	890	0.04
	Lubricating Oil	255	0.01
	PVC Tubing	2,600	0.1
	Urethane Foam	87	0.004
Blade Materials	Polyester Resin	5,160	0.2
	Glass Fibre	253,970	10
	Carbon Fibre	70,250	3
	PVC Foam	25,650	1
	Epoxy Resin	110,070	4
	Copper	694	0.03
	Low Alloyed Steel	2,840	0.1
Total		**3,967,870**	**160**

6.2.1 ScotWind Material Summary

A summary of all the materials calculated to be required to deliver ScotWind leasing rounds is provided in Figure 6-1.

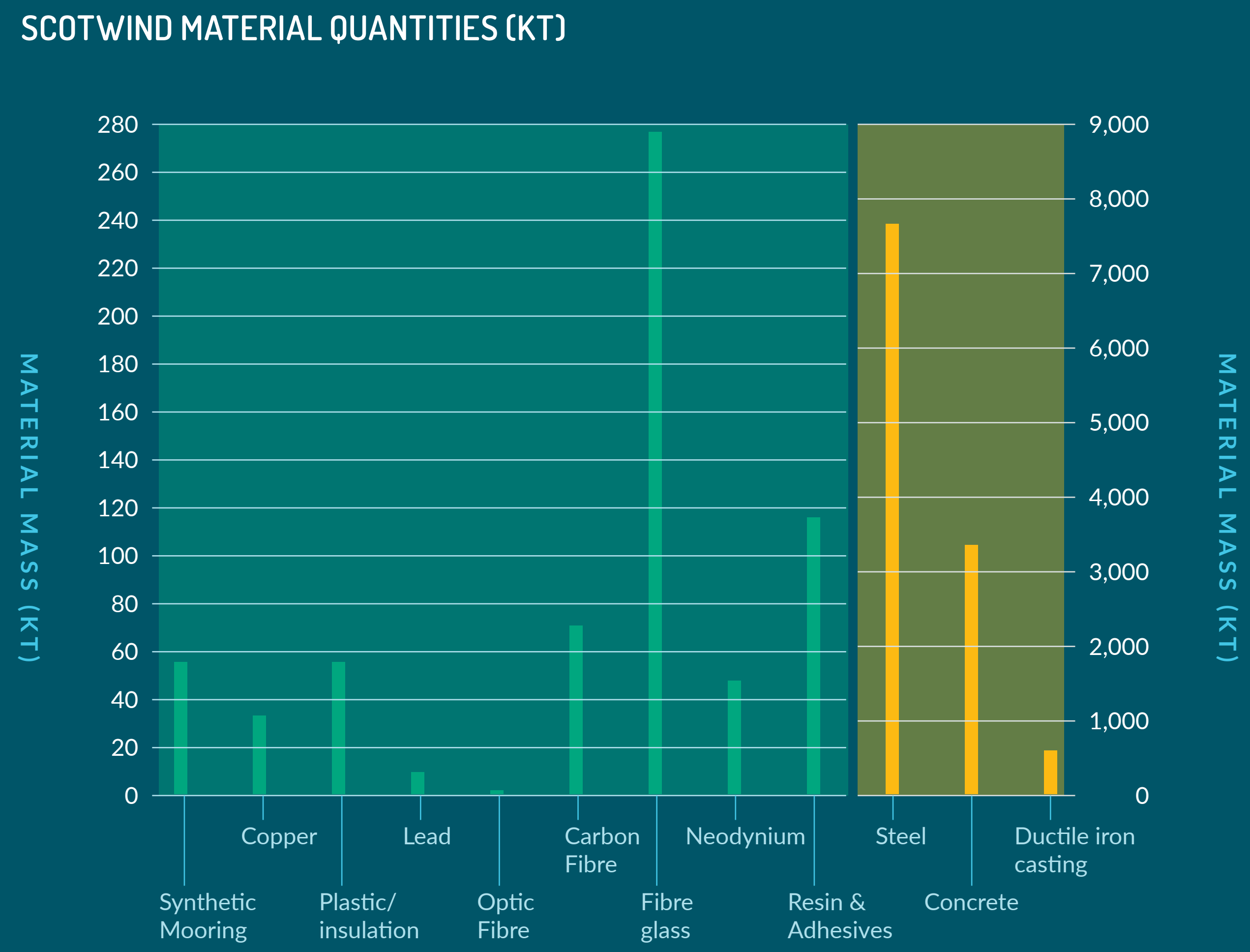


Figure 6-1 Summary of total ScotWind material quantities

6.3 FUTURE ASSUMPTIONS

The recent ScotWind leasing round has enabled the calculation of potential material requirements to complete each wind farm. This has been estimated through several factors including: knowledge of site conditions, the company involved in the development and the set guidelines for the specific leasing round. Each will have an impact on the material results involved. Looking to the future, beyond ScotWind, the information available for each site is significantly reduced, meaning more assumptions are required. This section explains the assumptions made for the upcoming INTOG round and the future outlook from 2035 to 2050, in five year increments.

6.3.1 INTOG

The next upcoming opportunity is the INTOG leasing round which is expected to open in 2022. Due to these sites not yet being leased, it is difficult to make accurate assumptions as to what the material requirements will be without first gaining details or making reasonable assumptions about each potential site involved. Although there is limited data available for the INTOG sites it is important to record whatever potential requirements there may be, as it is expected to be completed before ScotWind. This means that there will be greater urgency in the manufacturing and acquisition of materials to complete these wind farms within the desired time periods. To include the potential material requirements for INTOG the following assumptions were made to the calculations to offer a respectable representation of how these sites are likely to look. To achieve this, assumptions have been made in relation to the sites, popularity of design concepts and how dense the area is with O&G surface platforms.

From the initial framework published by the Scottish Government, INTOG will supply up to 500 MW of generating capacity for innovation projects, but each individual innovation project must not exceed 100 MW. However, the targeted O&G decarbonisation projects will have a combined target of up to 4 GW generating capacity and will not exceed 5.7 GW allowing for possible attrition [23]. Currently there are no estimations with regards to what capacities will be involved in each of the sites listed for INTOG, which are shown in Figure 6-2 in the blue hatched areas. Each INTOG site has been assumed to utilise floating substructures for both types of sites. A significant percentage of ScotWind is set to be floating structures, meaning this can be viewed as a build up to the larger sites involved in ScotWind, especially in relation to the manufacturing of floating platforms.

The Marine Scotland maps enabled estimates regarding the water depth of each site to be made and offered the number of surface O&G platforms within each INTOG site [3]. Crown Estate Scotland have stated that a “single large oil producing installation” requires a constant 24/7 load demand of around 40 MW, with a peak demand which comes during oil processing and export of approximately 60 MW [43]. This means that realistically all platforms will be expected to have a wind farm capable of supplying at least 60 MW of power.

Using the Marine Scotland maps to determine the number of surface O&G sites in each site, it allowed a reasonable assumption to be made about the required capacity of wind farms in each area to supply the O&G platforms. This is subject to a fixed point in time and many platforms could be added or removed during the years it takes to build the wind farms. However, this provides a rational representation of the numbers possible within each site. These numbers combined with the approximate water depth values of each site have enabled the calculations to be completed to estimate the material requirements expected by INTOG.

Regarding the innovation sites and any additional capacity remaining from the assumptions stated above for the O&G platforms, remaining capacities were split regarding the overall site squared area. The innovation sites were split between

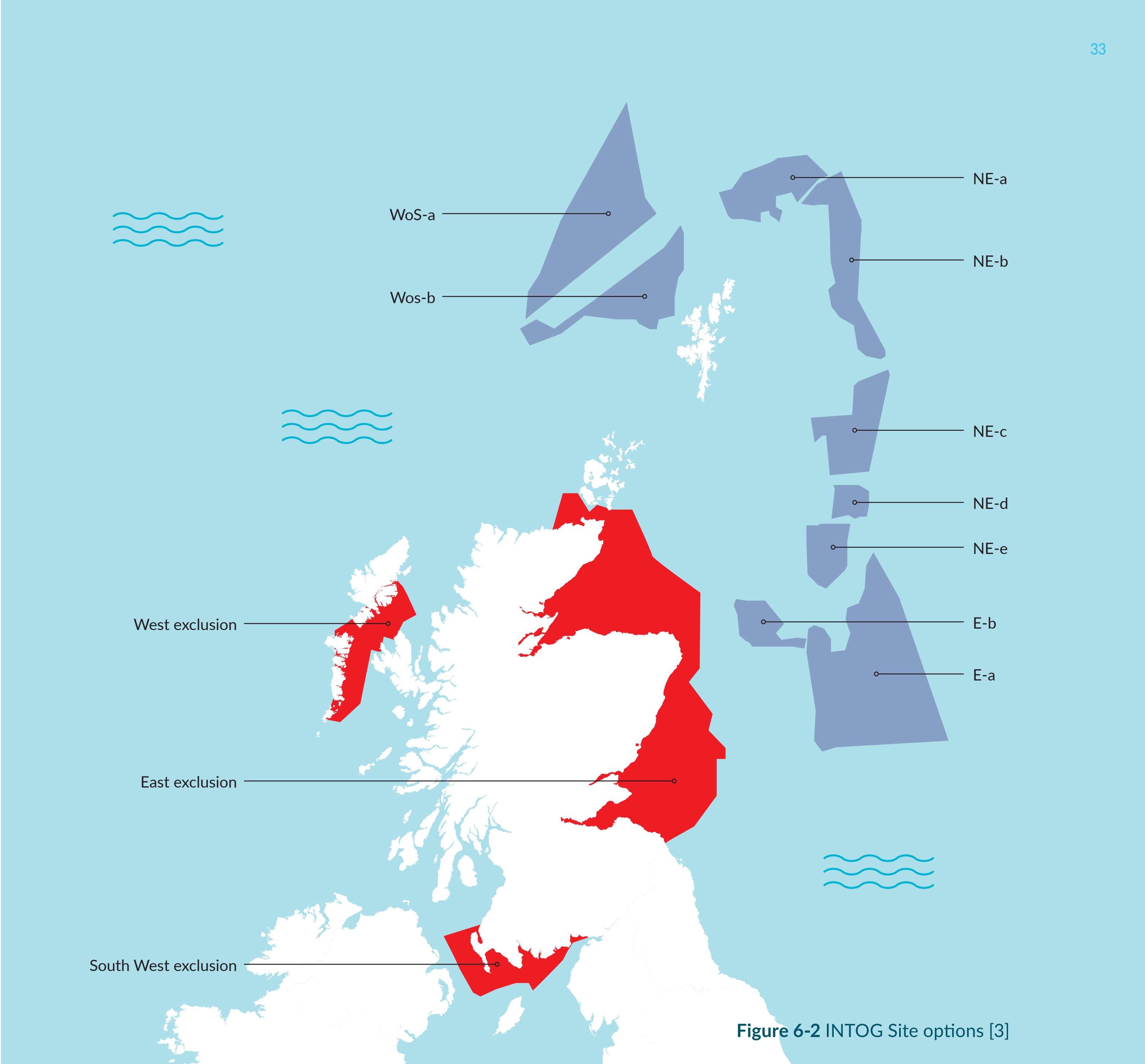


Figure 6-2 INTOG Site options [3]

three regions which all currently have no surface O&G platforms recorded in the Marine Scotland maps. The intention of INTOG is not to install projects in all areas stated but to support the main aim of achieving Net Zero. Therefore, highlighting the likeliness that the areas with an increased O&G presence are expected to receive increased installations of offshore wind.

The final estimated site capacities and water depths are shown below in Table 12. The sites which will host the innovation projects are labelled as “Innov” while the decarbonisation of O&G platforms have been called “DOG”. The combined 4.5 GW capacity set out for both projects is expected to be achieved due to the success of the recent ScotWind leasing round. All substructures have been assumed to be semi-submersibles as they are currently the most dominant of floating substructure designs and are expected to continue dominating, with more barge concepts being used in the future. The difference in average material requirements between a barge and semi-submersible design is generally low compared to any other designs, meaning that even as the number of barge designs increase the current mass used for semi-submersibles is applicable to both.

Table 12 Estimated INTOG data

Site Name	Site Type	Wind farm Capacity (MW)	Expected Typology	No. of turbines	Water Depth (m)
Ea	DOG	2,200	Semi-Sub	126	100
Eb	Innov	100	Semi-Sub	6	100
NEa	Innov	200	Semi-Sub	11	200
NEb	DOG	660	Semi-Sub	38	150
NEc	DOG	720	Semi-Sub	41	100
NEd	DOG	180	Semi-Sub	10	100
WoSa	Innov	200	Semi-Sub	11	1,000
WoSb	DOG	120	Semi-Sub	7	150
WoSc	DOG	120	Semi-Sub	7	400

6.3.2 INTOG Material Summary

A summary of all the materials calculated to be required to deliver INTOG leasing rounds is provided in Figure 6-3.

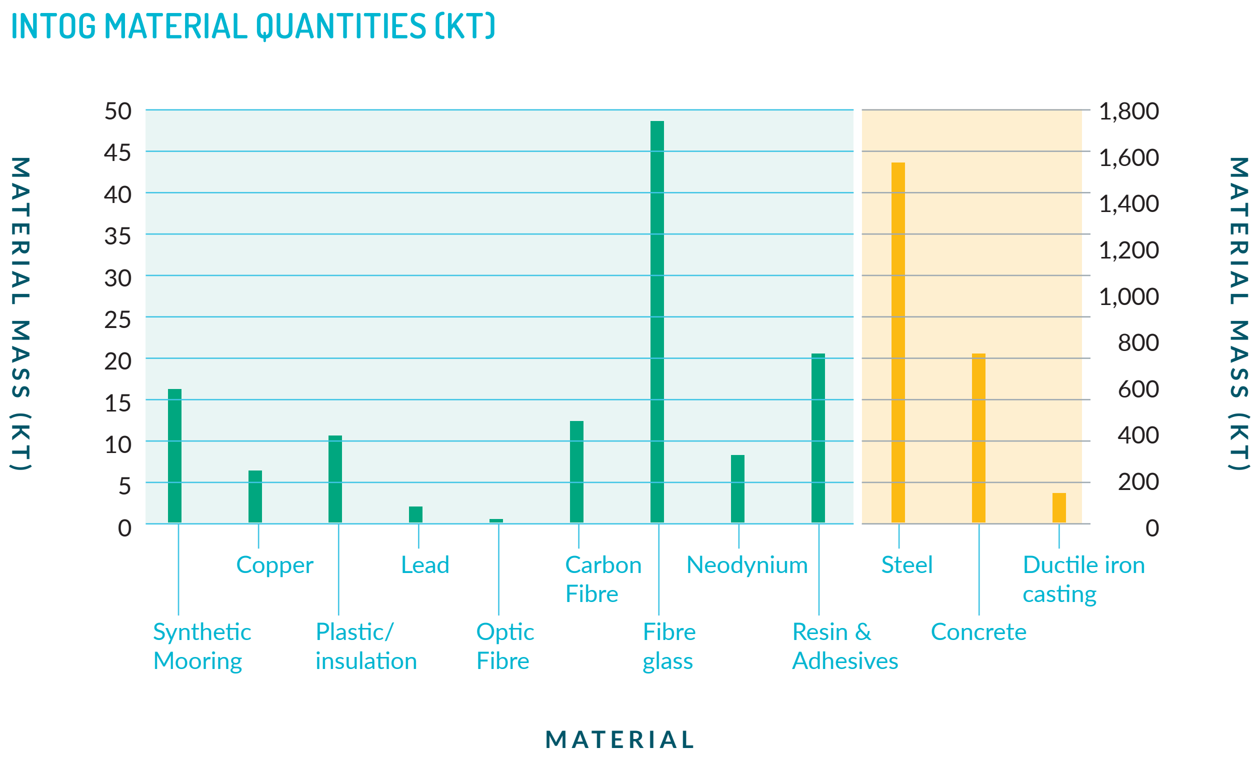


Figure 6-3 Summary of total INTOG material quantities

6.3.3 Future Outlook 2035-2050

Following the commissioning of the last few ScotWind projects, which are expected to be in the early 2030s, it can be expected that a form of gradual growth will progress as Scotland continues to offer new leasing rounds to meet the Net Zero targets set. The current expected deployment of offshore wind in Scotland from 2035 to 2050 in this section has been based on ORE Catapult's offshore wind future forecast as it currently sits for a predicted outcome of 100 GW of offshore wind across the UK by 2050. The forecasts used will likely increase in the future with respect to the results of ScotWind and recent UK Government announcements. However, as these numbers are based on current pipeline projections and include a steady growth of offshore wind up to 2050, the numbers are still representative for the current long term future outlook.

It is assumed that there will likely be no new fixed-bottom wind sites after 2040, as it is likely that most commercially feasible fixed-bottom sites will have already been developed. Potential fixed-bottom sites beyond this point would need to compete with floating wind sites, which are likely to have better wind resource and comparable or lower costs to build and operate. The assumed water depth for the 2035 – 2040 fixed wind deployment was set as 60m due to the limited compatible areas still available. The percentage of jacket to monopile foundations was set to follow the percentage split of the ScotWind foundation numbers, which resulted in a 60/40 split with slightly more jackets being installed.

It is expected that water depths could increase by a factor of 50m each five-year period as the deployment of floating wind farms is pushed into deeper sites which have yet to be utilised. The choice of material for a floating substructure is currently dominated by steel, but it is expected to even out as more concrete designs are deployed. Hence, from 2036 onwards we have assumed a 50/50 split between concrete and steel floating substructures. The uptake of concrete designs has been predicted due to the faster and simpler mass production processes involved. There are currently only a limited number of concrete designs that have passed the demonstrator stage; however, it is expected there will be an increase in popularity due to the reduced energy requirements involved in manufacturing and the possibility of using local resources compared to steel.

Table 13 Estimated future water depths for offshore wind farm development from 2036 – 2050

Scotland Water Depth Estimates (m)		
Year	**Fixed**	**Floating**
2036-40	60	100
2041-45	N/A	150
2046-50	N/A	200

The redevelopment and life extension of sites is likely to occur, but currently there are limited examples of any redevelopment of life extension in offshore wind. Therefore these potential implications have been excluded from the study. The aim is to highlight the potential material requirements to achieve the targets which have been set. The redevelopment and life extension of sites will ease pressure on material requirements, but this will have little impact on the upcoming wind farms due to the average design life being 25 – 30 years.

6.3.4 Future Outlook Summary

The total amount of material estimated to be required between 2035 and 2050 for each individual material type is shown in Figure 6-4. It is worth highlighting this is the first leasing round and period where a higher amount of concrete is required compared to steel as the shift towards concrete substructure becomes more dominant. There is also a significant increase in synthetic mooring as it is now industry proven. The breakdown for the mooring anchor and array cables is further detailed in Section 6.4.

FUTURE OUTLOOK MATERIAL QUANTITIES (KT)

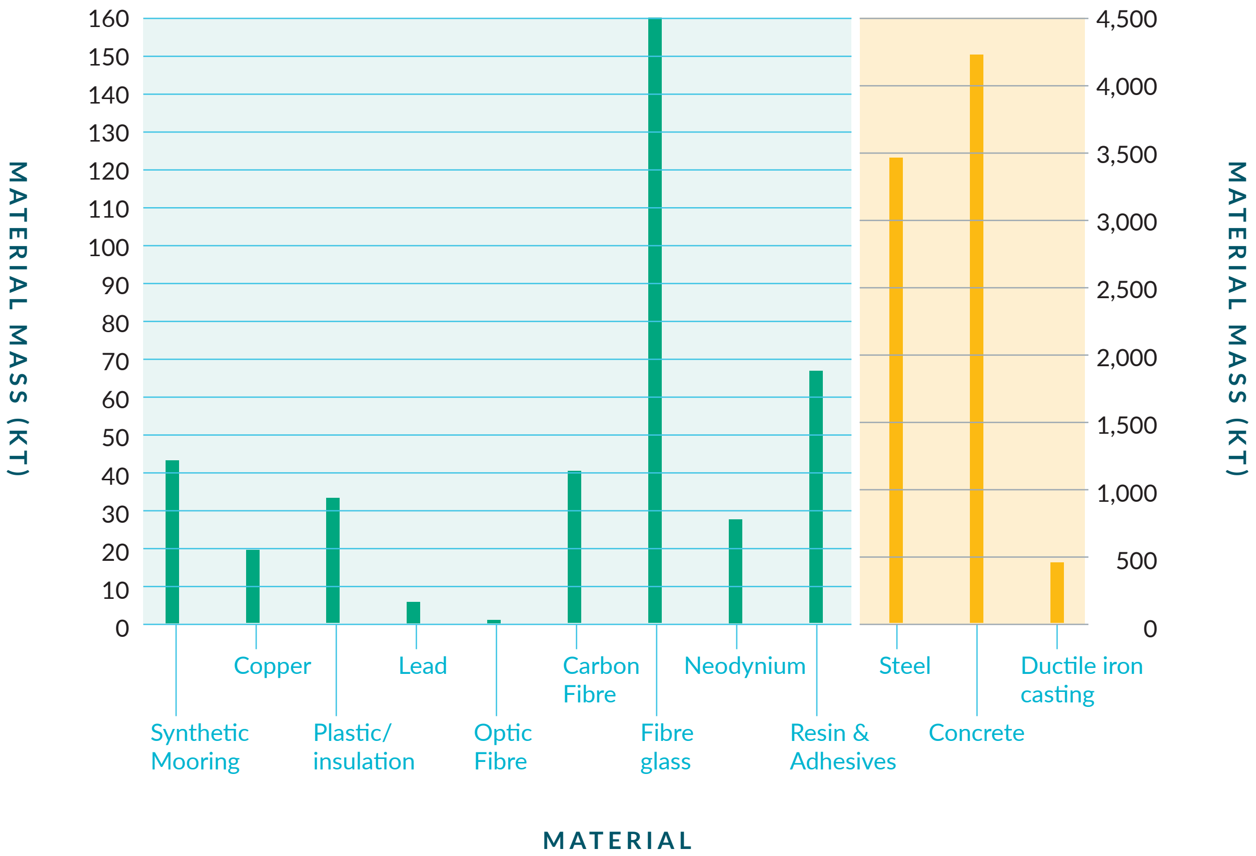


Figure 6-4 Summary of total Future Outlook material quantities

6.4
ANCHORS, MOORING & ARRAY CABLES

The output values for the anchor, mooring and array cables have been included in the previous summary graphs for each leasing round. The individual numbers which were included in the previous section are highlighted in Table 14 and Table 15. The following section explains the process used to calculate the anchor, mooring and array cable masses. Anchor and mooring configurations can vary significantly between different sites and substructure designs. There is also a lack of currently available dynamic cable data, along with a complex composition, meaning that assumptions are required across all wind farms to give a reasonable output. The mooring lines are all expected to remain as steel chain up until at least 2026, then a gradual shift towards synthetic rope is assumed to occur as its reliability is proven, meaning it will be utilised more across the industry. Steel drag embedded anchors have been assumed, as they are currently the most utilised and predicted to be the most common anchor used for offshore wind.

Table 14 Mooring line and anchor estimated material requirements

Leasing round/period	Steel chain mooring mass (t)	Synthetic mooring mass (t)	Drag embedded anchor mass (t)
Scotland (1,2,3)	13,680	0	3,420
ScotWind	530,880	55,040	141,120
INTOG	174,860	16,320	46,290
Future Outlook	183,240	43,820	109,080
TOTAL	902,660	115,180	299,910

Turbine spacing is also expected to increase as turbines increase in size meaning an increase in array cables. The values used regarding array cable topology and turbine spacing have come from ORE Catapult industry experience and research to give a general but realistic value.

Table 15 Array cable estimated material breakdown

Leasing round/ period	Conductor (t)	Insulation (t)	Lead Sheath (t)	Optic Fibre (t)	Armour (t)
Scotland (1,2,3)	10,250	18,070	6,750	1,130	35,720
ScotWind	14,370	25,340	9,460	1,590	50,090
INTOG	3,200	5,640	2,100	350	11,150
Future Outlook	9,140	16,130	6,020	1,010	31,880
TOTAL	36,960	65,180	24,330	4,080	128,840

07

SUMMARY OF MATERIALS

The total amount of materials currently installed before 2023 and the amount still required to complete the planned sites and future estimates are included in Table 16.

The total required column includes INTOG, ScotWind, future outlook (2035 – 2050) and the six wind farms still to be completed as part of the Scotland (1,2,3) leasing rounds. The assumptions and processes involved to make these predictions are detailed previously in section 5.1 and section 5.2. The total required steel is estimated to be 14.7 Mt. which is a considerable figure and includes all steel involved in the foundation, wind turbine, mooring lines and array cables.

Table 16 Total estimated materials currently installed and required up to 2050

Leasing round/period	Total installed (kt)	Total Required (kt)
Steel	1,040	14,630
Concrete	0	8,350
Synthetic Mooring	0	115
Copper	7	70
Plastic/insulation	12	110
Lead	5	20
Optic Fibre	0.6	3
Carbon Fibre	7	140
Fibre glass	30	540
Ductile iron casting	80	1,540
Neodymium	5	90
Resin/Adhesive	12	230
Total	1194.6	25,839

The quantities shown in Table 16 highlight the sheer magnitude of materials required to complete the forecasted offshore wind demand. The steel still required to meet the demand is approximately 14 times greater than what has been installed currently in Scotland. The required neodymium is important to reference due to it being a Critical Raw Material (CRM). An increased uptake in concrete substructure designs and the adoption of synthetic mooring lines is also clear as, although Scotland currently does not utilise either in its offshore wind sector, and these will play an important role in the future. This switch to synthetic rope and concrete could offer potential benefits because the local supply chain may be able to play a bigger role.

The following figures show the spread of demand of each of the materials mentioned in Table 16 from 2025 up to 2050. Most materials follow a similar path as they each spike around the 2027-2032 years due to the high targets set out by ScotWind which aims to install almost 25 GW. Following the ScotWind installation there is a predicted continued requirement towards 2050 which will still require an investment in materials to continue the targeted installations to achieve Net Zero. But it is worth drawing attention to the sheer magnitude required to complete ScotWind targets. The most in demand materials are shown in Figure 7-1 and include steel, concrete and ductile iron casting. During the spike of ScotWind there will be a requirement of up to 4.7 million tonnes in a single year. Realistically this may be spread over a few years, but it still highlights how high the demand is expected to be around 2030.

MATERIAL REQUIREMENT 2025-2050

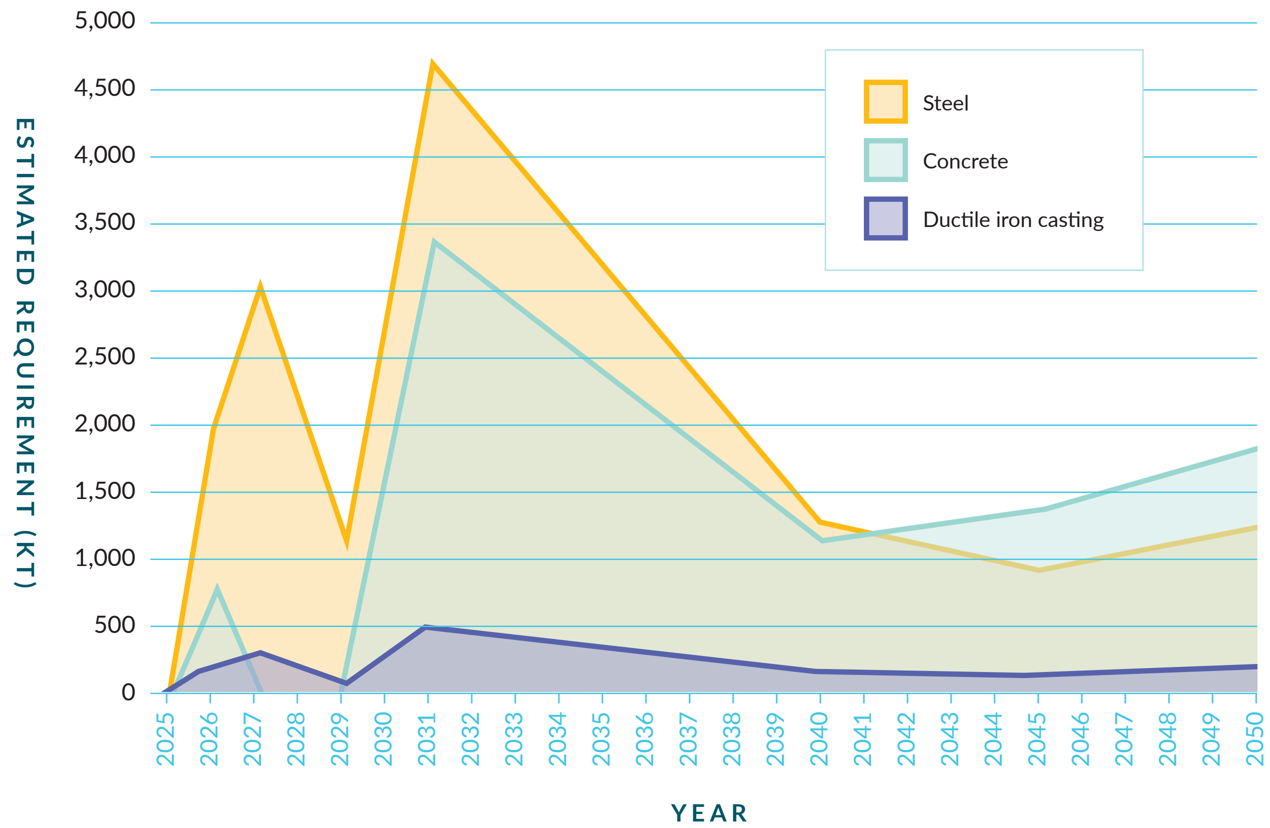


Figure 7-1 Material Requirement 2020-2050 (highest demand)

The next set of materials include fibre glass, neodymium and resins & adhesives. The requirement for these materials is much lower than in Figure 7-1, but these are still considerable quantities especially when factoring in the accessibility of neodymium and how copper can fluctuate on price and availability.

MATERIAL REQUIREMENT 2025-2050

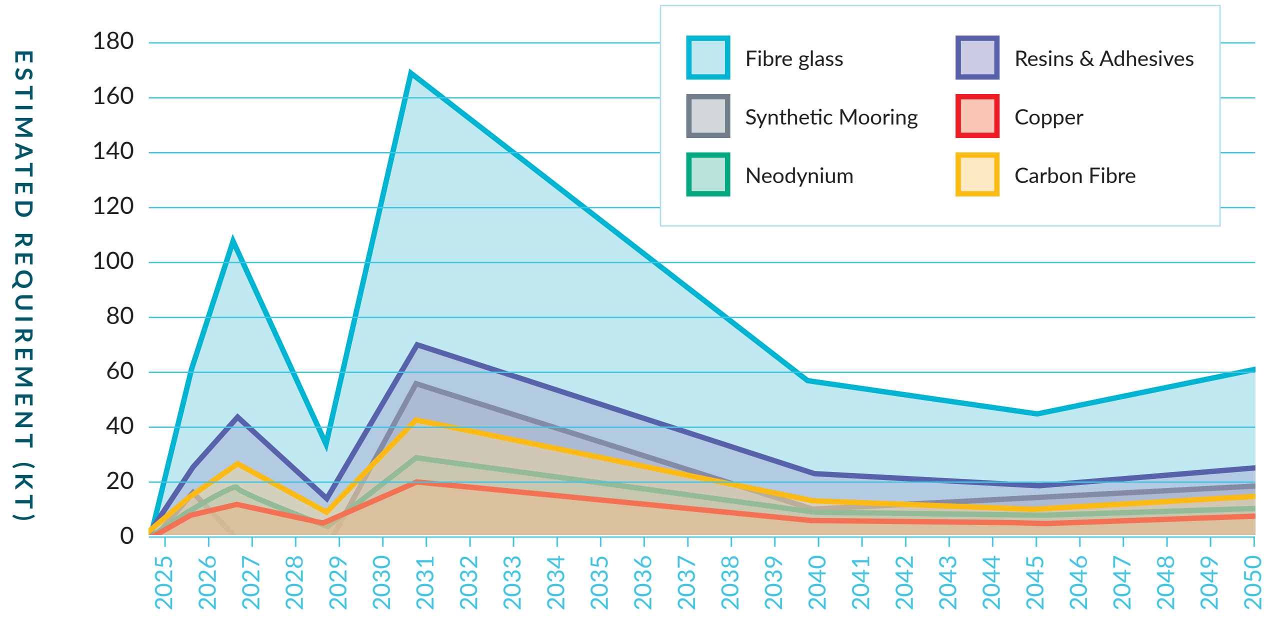


Figure 7-2 Material Requirement 2020-2050 (medium demand)

The lowest required materials include lead, optic fibre and the plastics / insulation. The spread of requirement up until 2050 is shown in Figure 7-3. Although these are the lowest required of all materials involved, these are still substantial amounts, needed for Scotland to achieve its predicted targets. The demand is similar to the previous figures as the main spike occurs due to the high ScotWind targets which are followed by a consistent demand of approximately 2 kt of lead and 5 kt of plastic / insulation. The uptake in synthetic rope expected during ScotWind is also clearly shown as it is only beaten by the 170 kt of fibre glass needed.

MATERIAL REQUIREMENT 2025-2050

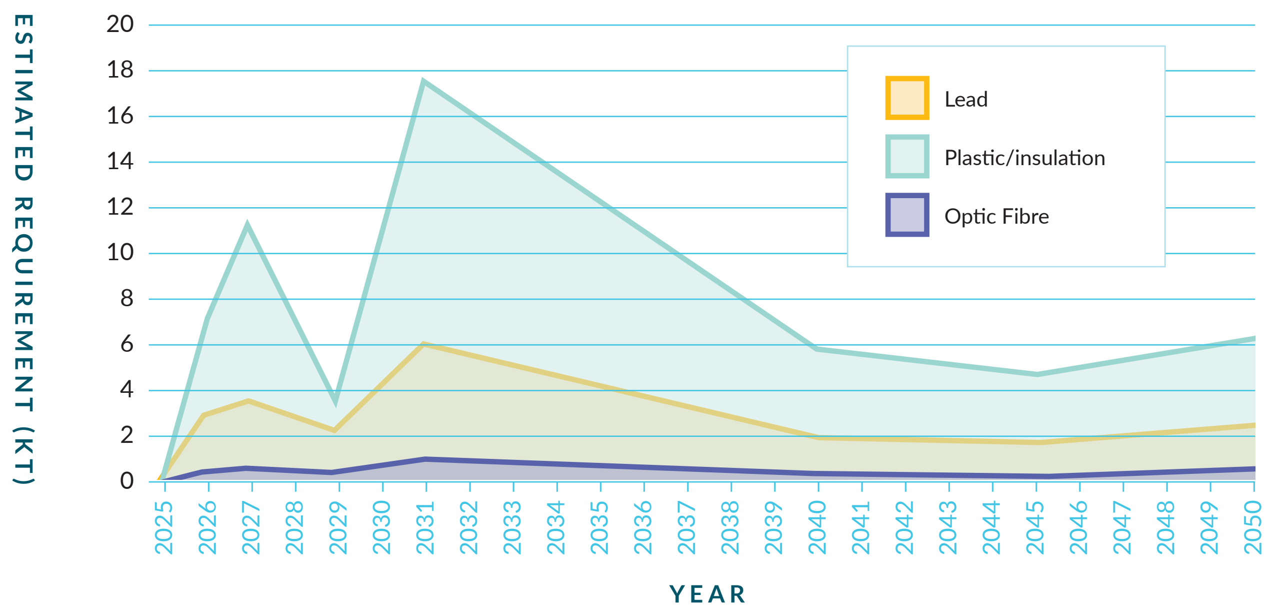


Figure 7-3 Material Requirement 2020-2050 (medium demand)

08

MATERIAL ROUTE MAPS

The philosophy of a circular economy is to design out all waste right from the start. It is the ultimate end point of this journey but one that will not be achieved imminently.

Future developments are already investigating waste reduction during manufacture, designing for repair and refurbishment through modular assemblies and researching alternative materials for easier separation and reclamation of materials at end-of-life. Zero Waste Scotland's Energy Infrastructure Materials Mapping [44] looks at the supply and demand of materials needed for construction and generated by decommissioning energy installations during Scotland's transition to Net Zero by 2045 for nine technologies, including offshore wind.

NEW WIND FARMS CURRENTLY IN PLANNING OR UNDER CONSTRUCTION WILL LIKELY BE BUILT WITH A LONGER EXPECTED DESIGN LIFETIME

The first step in the waste hierarchy (Figure 3-3) and the current best solution for existing operational assets for most, if not all operators, is asset life extension. Discussions during stakeholder engagement currently indicate that many operators will try to extend the operational life of existing assets, with a design lifetime of 20-25 years, by between 5-10 years. Additionally, new wind farms currently in planning or under construction will likely be built with a longer expected design lifetime, potentially 30-35 years, which will also likely be extended by 5-10 years. However, there is currently no formal guidance or legislation in place and these discussions remain speculative for the time being.

Partial or full repowering of whole wind farms and a host of refurbishing, reuse and remanufacturing approaches should be considered before instigating recycling, other forms of energy or material recovery and eventually disposal of materials.

If the wind industry is to have security of supply in the coming years and achieve the deployment targets set by UK administrations, establishing reliable and efficient supply chains and recycling processes is a necessity. With that comes a positive financial case, as it is estimated that the resultant onward sale of materials could recoup up to 20% of the decommissioning costs [45] for an offshore wind farm, not to mention the financial benefits for the development of a circular economy supply chain focussed on remanufacture, refurbishment and recycling.

8.1
STEEL

Steel is a highly versatile and recyclable material. It contributes to at least 70% of the mass of a wind turbine [46], with a recent study suggesting that steel could make up over 90% of the total mass of a theoretical, future 20 MW turbine [47]. When substructures are also considered, the steel mass can account for up to 97% of an offshore wind installation. While it is technically possible for steel to be recycled in Scotland, currently the infrastructure and necessary supply chains do not currently exist to facilitate the mass recycling of scrap steel. In 2018, nearly 820,000 tonnes of scrap steel were exported from Scotland for remelting and reprocessing overseas in locations such as Turkey, Pakistan and Spain [21]. This loss of valuable materials from the domestic market presents a significant opportunity for development of the Scottish supply chain, and domestic production would produce significantly less Greenhouse Gas Emissions (GHGE) than importing globally manufactured steel.

It may be possible for some aspects of the steel structures to be reused as they are, though it is more likely that the material will be recycled and reprocessed into new structures. The rate of growth and demand for materials, as discussed in Section 3.2 and Section 6, provide the ideal scenario for recycling decommissioned wind turbine structures into new, large capacity offshore wind turbines.

A new report from Zero Waste Scotland, *Energy transition assessment of adopting electric arc furnace (EAF) technology in Scotland*, proposes that the development of an EAF could produce Scottish steel from 100% recycled scrap, create high skilled green jobs, reduce GHGE and retain valuable material resources within Scotland [21]. By manufacturing steel domestically, companies would save the time, cost and GHGE from exporting scrap and re-importing remanufactured steel. This proposal becomes even more interesting when considered in conjunction with the Offshore Wind Sector Deal, where the industry committed to increasing the UK content of offshore wind farm developments to 60% of capital expenditure by 2030 [48].

8.2
MECHANICAL COMPONENTS

Mechanical components, such as gearboxes and bearings can contain many alloys of different metal elements, suited to their application. These often include carbon, chromium, manganese, molybdenum, nickel and aluminium, among others [49]. As there has been no large-scale decommissioning of wind farms in the UK to date, the question remains as to how these highly engineered components will be handled at end of life. The current options discussed are:

- If the turbine is otherwise in good working condition, it may have some value within the second-hand turbine market, such as in Eastern Europe, Africa or India and could be exported for a second life.
- The components are still considered to be valuable engineered units and are therefore separated from the general metal waste and sent for refurbishment and reuse, potentially as replacement parts in other wind farms.
- If wind turbines are no longer considered as a viable operational asset and the components cannot be reused as replacement parts at other wind farms, there may be limited applications for reuse or remanufacture within other industries.

Once reuse and remanufacturing are no longer options, they are considered as end of life parts, only worth their scrap metal value. In this incidence, they are not likely to be separated from the general scrap waste pot on decommissioning and will be sent for recycling along with the rest of the carbon steel structural materials. The alloys in these materials do not raise any concerns for the steel processing facilities, as long as no copper is mixed into the melting pot. Even small quantities of copper can cause series problems with contamination and careful separation of electrical components and wires from the scrap metal is required.

8.3
ELECTRICAL COMPONENTS

Electrification has become a crucial aspect of the energy transition to meet Net Zero and decarbonisation targets. From the UK's energy generation infrastructure, transportation, manufacturing processes and the drive towards automation and robotics applications. As a result of this, there has been a significant increase in the demand for the Rare Earth Materials (REM), such as those found in permanent magnets, that are essential for the manufacture of energy transition technologies.

Following discussions with stakeholders, there is a potential gap in the market for the end of life handling of electrical components. The general expectation is that all metal components will be cut down and shredded. This destroys any magnets, such as those in the turbine generator and motors, losing these valuable materials from any potential reuse.

High performance applications require greater magnetic energy density from magnets made with alloys of neodymium, iron, boron and dysprosium, particularly for high temperature applications [50]. It is technically challenging, energy intensive and often acutely harmful to the environment to mine and produce the pure single-element powder required for magnet production [51]. Recycling and reusing the resources that have already been extracted, processed and manufactured provides both a significant environmental advantage but also proposes to be of considerable economic benefit, reducing reliance on potentially turbulent international trade.

There are several companies in the UK developing effective methods for recovery of REM from electronic equipment and reforming them into high-power, high-grade magnets for reuse in a variety of industry applications [52] [53].

However, these processes rely on magnets successfully being recovered from equipment before it passes through a shredder. A critical intervention will be required during decommissioning to ensure that these essential materials are recovered. However, there are serious challenges with transporting magnetised equipment, which can often be classified as "dangerous goods". High powered magnets can be extremely hazardous to anyone with a pacemaker or several other medical implants [54]. Packages containing magnetic materials must be clearly identifiable and a Declaration of Dangerous Goods provided to the courier. This not only leads to increased shipping costs, but an additional Dangerous Goods fee may also apply [55].

Although we have the capabilities to manufacture magnets in the UK, we have no manufacturing facilities for wind turbine generators in the UK. Therefore, magnet manufacturers in the UK aiming to sell their products to wind turbine OEMs may be limited to the REM recovery, processing and reforming, with the final magnetisation step completed by the OEM or nearer to generator manufacturing facilities, such as those in Denmark, Germany and Spain.

One project that has made progress recycling electronic waste is the UK Royal Mint. It has developed plans to establish a new facility in South Wales for the recovery of gold, primarily from the circuit boards of small, personal electronic equipment such as mobile phones and laptops [56].

8.4 COMPOSITES

A key focus for the offshore wind industry is finding a sustainable solution for recycling composite materials, primarily the wind turbine blades. The blades are typically constructed of a polymer resin matrix that is reinforced with glass fibres, with carbon fibres also used in longer blades. A laminate core material, often made from high density foam or balsa wood, provides additional strength, while maintaining a lightweight structure. The exterior of the blade is coated for weather protection and improved aerodynamic performance and there are also some metal components associated with the lightning protection system, which prevents damage to the blade in the event of a lightning strike. This complex combination of materials makes it difficult and historically, not cost effective, to separate and recycle the constituent parts. Nevertheless, there is significant interest and effort from across the sector, academia, industry and Governments to find a solution to this challenge.

A collaborative report published last year by ORE Catapult for the Energy Transition Alliance, identified over 28 research projects in this area alone, covering material separation trials, to demonstration projects that utilise whole blades or sections [12]. The wind sector (on and offshore) is expected to decommission 40,000 to 60,000 tonnes of composite materials by the end of 2023 alone [57]. There are three main forms of material reclamation recognised and actively under investigation: mechanical, thermal and chemical. However, once fibres and other materials have been separated and recovered, further steps are required to reprocess them into usable materials which can be recycled in the manufacture of new products and components across a wide range of industries [12].

OEMs are actively seeking to remove this problem from future turbine designs, by investigating alternative materials so that blades are designed to be more easily recycled right from the beginning. Resins that melt at lower temperatures to reduce any potential heat damage to fibres during pyrolysis processes and bio-resins, made from natural polymers are just two examples [58] [59] [60].

09 FUTURE OPPORTUNITIES FOR CIRCULARITY

9.1 LEVELISED COST OF ENERGY POTENTIAL

An ORE Catapult Analysis and Insights report on comparison of end of life strategies for a representative UK offshore wind farm showed that partial repowering is the most profitable option for the developer who can upgrade the turbines and so can maximise its electricity production with low overall extra cost [20]. Life extension was the second most profitable strategy with the lowest extra cost among all scenarios but also preserving the same annual electricity production for another 10 years. Full repowering is also profitable but, to a less extent, because it includes the replacement of foundations and cables. Decommissioning does not generate any revenue, so it is the least preferable option.

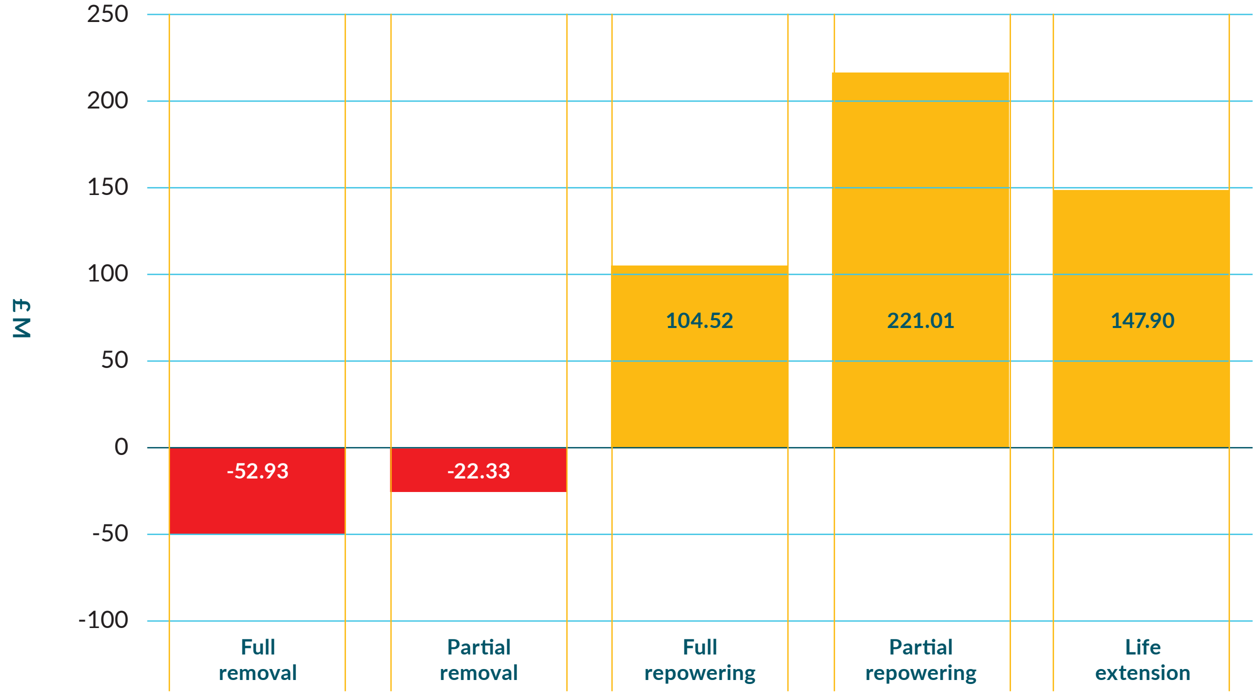


Figure 9-1 NPV comparison of end-of-life scenarios

There are already companies demonstrating the significant Levelised Cost of Energy (LCoE) Potential for using refurbished components and recycled materials, some case studies of which can be seen in Section 11.

9.2 EMBEDDED CARBON REDUCTION POTENTIAL

The traditional linear approach to manufacturing where products are disposed of after use, along with the environmental impact concerns, has led to a high loss of valuable materials which are usually imported. The transition to a circular economy model would minimise the volume of resources taken from the natural environment, maximise the prevention of waste and optimise their economic, social, technical and environmental values throughout consecutive lifecycles [61]. Reuse and recycling should always be considered as the best options after the end of operational life of an asset or component. Demand for used onshore wind turbines and components is high in developing countries offering fast delivery and cost saving of up to 40% compared to new turbines [62]. A similar action could be adopted in offshore wind at large scale to help accelerate its deployment to emerging markets which lack the adequate resources. Components can also be utilised for alternative application from their original manufactured purpose, for example, wind turbine blades remanufactured and used as bike shelters and playgrounds [63] [64].

If reuse cannot take place, then recycling is considered the next best option. Theoretically almost 90% of a wind turbine can be recycled, although there are complications in terms of efficiency, cost, value, availability and lack of guidelines that reduce this percentage in practice [11]. Materials like steel and copper can be scrapped and recovered with no or partial loss of their primary material value. Steel is the most recycled metal in the world, while premium-grade copper holds 95% of its value after recycling compared to original primary material [65]. By feeding back these materials to new manufacturing, not only will this reduce waste and the environmental impact of decommissioning but will also reduce the reliance on material imports and the leak of valuable funds.

Table 17 and Table 18 below and opposite show the mass proportion, total carbon content and saving from primary and recycled materials of Scottish offshore wind turbines by 2050. The analysis showed that steel (including foundations) represents up to 90% of the total mass and contributes 82% to the total GHGE.

Table 17 Breakdown of mass of main materials used in Scotland's offshore wind turbines by 2050

Material	Mass (t)	Mass %
Steel	13,899,320	88%
Copper	27,060	0.2%
Ductile iron casting	1,156,960	7%
Other materials	805,190	5%
TOTAL	**15,888,530**	**100%**

Table 18 Carbon content of primary and recycled materials in Scotland's offshore wind turbines by 2050

Material	Primary carbon content (tCO2e)	Primary carbon content (%)	Recycled carbon content (tCO2e)	Recycled carbon content (%)	Carbon saving (tCO2e)	Average carbon saving (%)
Steel	33,956,780	70%	19,042,070	97%	14,914,712	32%
Copper	126,100	0.3%	22,730	0.1%	103,370	82%
Ductile iron casting	1,981,270	4.0%	601,620	3.1%	1,379,653	70%
Other materials	12,859,910	26%	-	-	-	-
TOTAL	**48,924,060**	**100%**	**19,666,420**	**100%**	**16,397,735**	**34%**

Carbon saving analysis used ORE Catapult's in-house LCA model in combination with embodied carbon conversion factors from the Inventory of Carbon & Energy (ICE) database published by Circular Ecology to estimate the carbon saving potential for each material after being recycled [66]. According to this analysis, carbon savings would mainly derive from the use of recycled steel with a small contribution of copper and cast-iron back to new manufacturing and estimated as 34%.

In terms of value recovery potential, steel is 100% recyclable and scrap is converted to higher or lower grade steel depending upon the metallurgy and processing of the required product [67]. Scrap steel has a relatively high economic value (£230 per tonne in January 2021), so in the case of Scotland's offshore wind turbines the estimated value of recycled steel is estimated at up to £3.2 billion. Likewise, premium-grade scrap copper holds around 95% of its value after recycling. It is present in a small amount of the overall turbine mass, but it is a key material of the electrical parts in the nacelle. The carbon saving of recycled compared to primary copper can reach 82% confirming its high recyclability. The economic value of recycled copper in this analysis was estimated to be £166 million. Cast iron contributes less than 0.5% of the total turbine mass, so despite its high carbon saving potential (70%) there is no significant economic return from its recycling in offshore wind. Other materials like plastic polymers, carbon or glass fibre, lubricating oil and neodymium are currently either non-recyclable or complex and costly to recover, so these were not included in the carbon saving estimates from recycling materials.

9.3 ECONOMIC AND JOB CREATION POTENTIAL

Research from the University of Leeds into the economic and employment opportunities for a circular economy provides interesting insights. Their model identified that, while job creation is limited for tasks involved directly in life extension and repowering, there is significant opportunity for 5,000 jobs to be established in the UK with regards to remanufacturing and refurbishment [16]. This confirms the discussions held during the stakeholder engagement that it is highly likely that a third sector will develop in the circular economy supply chain for the long-term O&M and life extension of wind farm operation.

Additionally, early estimates predict the potential creation of up to 20,000 jobs by 2030 with the development of a full UK circular economy supply chain, including a wide variety of recycling processes for the full range of materials [16].

10

CONCLUSIONS AND RECOMMENDATIONS

KEY FINDINGS:

By 2050, it is currently estimated that up to 492 turbines will be decommissioned in Scotland, increasing by an additional 1,718 by 2065

Offshore wind decommissioning in Scotland could generate between 1.5 million – 2.4 million tonnes of materials by 2050

By mass, steel is the largest proportion of material from offshore wind farm decommissioning, which is currently mainly exported for recycling

By 2050, it is estimated that to achieve the expected growth of offshore wind it will require approximately 14.7 million tonnes of steel, 8.36 million tonnes of concrete and 1.54 million tonnes of ductile iron casting

By 2050, it is also estimated that some of the other consumables required to complete the expected offshore wind growth include 682 thousand tonnes of glass and carbon fibres, 93 thousand tonnes of neodymium and 67 thousand tonnes of copper

CONCLUSIONS

What could a circular economy mean for the offshore wind sector?

34% embodied carbon saving if new turbines are manufactured using recycled content

Solutions such as refurbishment, remanufacture and recycling could create up to 20,000 high skilled green jobs across the UK

Scalable opportunity with the volume of projected offshore wind growth

Safeguards against future shortages of critical Rare Earth Materials (REMs)

Significant reduction to the offshore wind industry's carbon impact

RECOMMENDATIONS:

Raise awareness of the circular economy business opportunity with domestic supply chains and policymakers. As highlighted earlier, the opportunity goes beyond the basic concept of recycling; it spans various remanufacturing and reprocessing solutions for every wind turbine component. Investment now presents a golden opportunity to not only support the offshore wind sector's job creation targets by 2030, but to extend them by an estimated 20,000 jobs in a circular economy.

Investment in a new circular economy and recycling infrastructure, such as an Electric Arc Furnace (EAF), are essential to building capability and capacity to recycle wind turbines domestically and to meet the target of 60% UK content for future offshore wind developments.

Further studies and collaborations with OEMs would provide a significant contribution to supporting supply chain and market development of a third sector circular economy for life extension, remanufacturing and end of life management of materials.

Collaborative R&D programmes between industry and academia focussed on the development of innovative methods for material separation, recovery and reprocessing, with a particular focus on more sustainable practices than those currently in use. Feasibility studies can lead to funding to explore the development and demonstration of recycling processes for REMs from a variety of sources.

Supply chain development activities, connecting those with the "waste" to the companies with the refurbishment, remanufacturing or recycling skills and processes should be implemented. Establishing new networks of chemical and material sectors to manufacturers and end users will facilitate the exploration, development and integration of the circular economy opportunity across the supply chain.

11

CIRCULAR ECONOMY CASE STUDIES

11.1 RENEWABLE PARTS

Renewable Parts was founded in 2011 by Ewan Anderson as a supply chain and refurbishment specialist for the wind industry. Initially they traded in new parts and consumables, with refurbishment and remanufacture on the side. However, after observing the significant waste generated from wind turbine components being sent for scrap and landfill when damaged or at the end of their operational life, they were inspired to develop a more innovative and circular solution.

In 2019, Renewable Parts launched their Refurbishment Centre in Lochgilphead, with support from Zero Waste Scotland, to become an innovator in green technology for the wind industry driven by a philosophy of continuous improvement. Focusing on circular economy best practices, its specialist refurbishment centre is a central pillar of the company's vision to create a more sustainable industry.

By applying the latest techniques to restore unserviceable parts to their original "as new" condition, they are now helping their customers reduce their carbon footprint and become greener businesses. This pioneering work has resulted in multiple solutions across technologies including Vestas, Siemens-Gamesa, Senvion, Nordex and GE technologies [68].

GROWTH AND FUTURE EXPANSION

Over three years, Renewables Parts doubled in size from 15 employees in 2019, to 30 employees in 2021. They are expecting to double once again over the next two years and potentially triple over the next five years, aiming by 2027 to have appproximately 90 employees.

Growth in staff also led to the creation of a new purpose build facility in 2021. The company's new Innovation Centre increases their premises to 5,000 square feet (sqf) and demonstrates their expanded focus on manufacture and redesign of refurbished and replacement parts. In 2022, they are planning the acquisition of new premises in Renfrew, leading to an almost fivefold increase in premises to 24,000 sqf. This new site will host their Operations Centre, which is expected to hold stock for the Innovation Centre. At the time of writing, renovation is ongoing with the aim to move into the new site by summer 2022.

Renewable Parts has successfully collaborated with developers across the industry. For example, one such success story was the creation of a redesigned yaw dampening kit after months of close work with SSE. Renewable Parts has also had active academic engagement with the University of Strathclyde since 2019, and their collaboration revolves around the remanufacturing and stress testing of parts. A Knowledge Transfer Partnership Award was granted in 2022 to further their work over the next two years.

Renewable Parts also has a keen interest to expand abroad. Owing to predicted demand, it is hoped that a new refurbishment or innovation centre could be established on the European mainland. Spain has been identified as the likeliest site for onshore wind, but Denmark and Norway are also being considered. There are also aspirations to expand to North and South America.

ENVIRONMENTAL IMPACT

Renewable Parts has been responsible for a massive CO2 reduction by saving material going to landfill. Between 2019 and January 2022, they diverted 111 tonnes of waste/scrap from landfill. Utilising a carbon calculation from Worldsteel of 1.8 tonnes carbon reduction per tonne of steel [69], they are responsible for a CO2 emissions (CO2e) reduction of approximately 200 tonnes.

The company is currently measuring their overall carbon emissions, to help them achieve their goal of becoming completely carbon neutral by 2025 and it is hoped they will be carbon negative by 2030.

INDUSTRY IMPACT

Renewable Parts aim to lead a culture change within the industry, demonstrating the effectiveness of a refurbished part compared to new. They can reduce cost, time and environmental impact for their customers by providing remanufactured components that are "as good as new". Additionally, their significant work on R&D ensures that the performance of any refurbished part will match or be better than the equivalent new part. Their business model prioritises minimising waste and keeping turbines running for as long as possible, supporting operators with life-extension and increasing operational lifetime from 20 years to 30 or 35 years in the future.

The company also runs an effective supply chain service to several customers that have turbines approaching the end of their service life and is already helping them deliver life extension of operation. Combining their refurbishment process with an in-house inventory management system, they can reduce both cost and lead times within the industry, reducing downtime and increasing energy revenue.

There is also enormous potential for their work to positively impact a projects' LCoE. If Renewable Parts were adopted across the industry, their cost-effective refurbishment would reduce both initial investment and O&M expenditure, resulting in a lowered LCoE.

FUTURE CHALLENGES

One of the biggest challenges is changing customer habits to favour re-use over buying new products. To help build trust in refurbishment, Renewable Parts believes there must be standardised certifications such as an 'As New Warranty'. They have been in talks with both the Scottish Government, as well as all major political parties in Holyrood, to push for stronger industry regulations.

One decommissioning option considered has been to sell turbines second-hand to developing countries. However, this could be prohibitively expensive. The cost of repairing and maintaining older turbines in countries with a smaller renewables industry and more restricted access to tools and resources would be prohibitive. To overcome this, there would need to be an agreement framework to share necessary O&M manuals, material information and a wider circular economy both within the UK and the developing countries.

11.2 REEKIE MACHINING

Reekie Machining is a third-generation family business founded in 1946, designing and manufacturing portable machine tools. They originally supplied services to the power and shipping industries, where the need to repair large pieces of unmoveable equipment led to them pioneering in-situ manufacturing in the UK. Although their initial focus was on the design and manufacture of equipment which could complete repairs on site, they found themselves increasingly supplying both service and technicians to their clients.

Their early involvement with the offshore wind industry began in the 1990s, when they were able to provide a like-for-like repair to a fault in a wind turbine tower. Having contributed to the repair and continued operation of both onshore and offshore wind turbines for three decades, Reekie have grown particularly active in the industry since 2015 through the development of bespoke equipment and processes.

GROWTH AND FUTURE EXPANSION

As a family business, there were few employees when Reekie Machining was first established. Now they employ approximately

60 staff, with small seasonal fluctuations, and all employees are fulltime and local. In line with their five-year growth plan, the company aims to double its turnover to over £10 million annually and predict that this is fully achievable with the addition of approximately 10 new employees.

As leaders in the field of In-Situ Machining, Reekie also offer additional services of hydraulic torque and tensioning, laser alignment and leak sealing as they believe that the industry requires more than just machining to fully support the client. Lately there have been increasing enquiries from new companies for alternative solutions within nuclear power generation, offshore, renewables and shipbuilding. This is a hopeful sign for the future, both for the business and for a more circular economy, offering greener and environmentally friendly solutions.

ENVIRONMENTAL IMPACT

Reekie Manufacturing has also worked with Scottish Power to design equipment for the repair of damaged wind turbine yaw gears. Typically, a repair to a yaw gear would require the whole rotor and nacelle to be removed, the damaged component to be extracted and a new replacement gear to be installed before the turbine can be reassembled. Reekie's methods allow for the gear to remain in place during repairs, removing the need for substantial craneage and multiple, complex lifting operations. Additionally significant material savings are made as only the damaged part of the component is disposed of and a whole new component does not need to be manufactured. This can reduce the new material required by approximately 80-90% whilst ensuring that any material removed from the damaged section is captured and recycled. Furthermore, there is an estimated schedule reduction of 80%, which reduces the carbon emissions from vessel and crane operations during repairs.

In collaboration with an offshore wind turbine installer, Reekie Manufacturing has proposed bespoke equipment to cut and remove monopiles from the seabed by using water jetting technology. This would make use of water at ultra-high pressure, entrained with silica, which eliminates the need for any chemicals and substances during decommissioning. The process could also remove the tower from a level below the seabed, which ensures that 100% of the material from above ground could be recovered and recycled. The ability to cut the tower into small pieces would also reduce the reliance on larger vessels, also leading to reductions in carbon emissions in the future.

INDUSTRY IMPACT

Repairing the damaged yaw gear rather than replacing it, negates the need to manufacture, machine and transport the new gear offshore. It also eliminates the need to dismantle the turbine to remove the damaged part, which currently requires the rotor and the nacelle to be removed, which would eradicate the need for any cranage or large lay down space on vessels. The number of personnel and scale of support vessels would also be significantly reduced. Additionally, the estimated schedule reduction would dramatically reduce downtime as operational windows are substantially increased and repairs are not restricted to low wind crane operations. Altogether, this procedure could deliver huge cost savings while limiting waste, reducing downtime and minimising health and safety risks.

Compared to traditional gas axing methods, it is estimated that Reekie Manufacturing's water jetting method could reduce the decommissioning schedule by as much as 30%. Cost savings would also come from operations, removing the need for any gases or chemicals and a reduction in project duration. This would help to reduce the cost for decommissioning as well as decrease health and safety risks.

FUTURE CHALLENGES

Reekie see one of their greatest challenges as meeting new contacts and getting their message out to potential end users, whether that be the owner operator of the wind farm, the service contractors who manage installation, or the decision makers themselves. As the Covid-19 pandemic has limited face-to-face meetings, they have found it difficult to break into the industry as they are often only contacted when a client specifically needs something.

Nevertheless, they believe that they will have greater luck with establishing and selling their solutions once the development phase for their monopile solutions is completed. It is expected that a greater push for decommissioning will attract customers, especially once trials demonstrate the potential of their designs.

11.3 GEN 2 CARBON

"Recycled Carbon Fibre" was established in 2003 with a focus on developing methods for recovering carbon fibre from composite waste. They established the first industrial scale carbon fibre recycling plant in 2009, recovering fibres by pyrolysis and converting them to milled carbon fibre. They were acquired by ELG Haniel and became "ELG Carbon Fibre" in 2011, expanding the output of the recovery process to include chopped and nonwoven carbon fibre products in 2015 in anticipation of future market demands. Gen 2 Carbon grew out of ELG Carbon Fibres as an independent business in April 2021, focused on the development of next generation carbon fibre recovery systems and the expansion of carbon fibre nonwoven business.

Now, the company aims to support the transition to a more circular economy by recycling carbon fibre from wind turbines back into the renewables and other sectors. Both the global demand for carbon fibre and the waste from carbon fibre products has grown and continues to grow. It is anticipated that waste will increase from 56,000 tonnes in 2021, to more than 100,000 tonnes by 2030. Currently less than 1,000 tonnes of this is recycled and returned to the market, although recycled carbon fibre is technically capable of meeting around 20% of projected carbon fibre demand.

The carbon fibre manufacturing industry lags behind others such as the aluminium industry which has managed to grow substantially more over the last 20 years, due to the significant volume of material recycling, which has also led to a considerable cost reduction for aluminium production. By contrast, the carbon fibre industry has not yet taken advantage of recycling technology and innovation, which is where Gen 2 Carbon seeks to fill the gap in the market.

GROWTH AND FUTURE EXPANSION

Gen2 Carbon counted 24 employees in April 2021, and at the time of writing, their facilities are responsible for the production of approximately 90 tonnes of recycled carbon fibre products a year. Their core plan is to focus on delivering existing products to existing customers, with an aim of dramatically increasing their production to 600Te / year by 2025. Gen 2Carbon believes that the carbon fibre market is unpredictable, but nevertheless hopes to deliver new products where they can. One example is supporting a company with their in-house development of electrodes, which they estimate would require around 1,000 kTe a year.

They have a strong R&D focus on developing products specifically for clean energy applications, such green hydrogen production, hydrogen power systems and grid-scale storage solutions. Gen 2 Carbon has been collaborating with several RTOs and academic institutes to help broaden their expertise in these fields. These partners include the universities of Birmingham, Brunel, Oxford, Nottingham, Warwick, Oxford Brooks and Bristol in the UK, as well as overseas institutions such as Fraunhofer and Deakin University.

Gen 2 Carbon hope to expand into new facilities over the next two years, through a series of modular plant designs, where they would establish new plants via licensing close to key sources of carbon fibre waste as well as anywhere there is sufficient demand for recycled products.

Thanks to a partnership in Australia, they are hoping to establish a facility with an initial 200 Te capacity which would be partly funded by the Australian Government and designed to support local manufacturing. A partnership with a European company has also seen them looking towards a manufacturing plant in China, as the local supply chain of natural fibres is well established compared to Europe. They would use a combination of recycled and natural fibre to help support the mass production of a new product expecting to be brought to market in 2023. Lastly, they have been looking to build a facility centred around Boeing in North America to help turn aviation carbon fibre waste back into the aerospace industry.

ENVIRONMENTAL IMPACT

They have also been undertaking small scale work with the University of Birmingham to trial the recirculation of syn gas (41%

hydrogen 14% methane). The hope is to collect and reuse the pyrolysis gas, with an expectation of recovering up to 3 kW of energy from the gases produced from each kW put into the process. While the method has yet to undergo Combined Heat and Power feasibility assessment, it hopes this will deliver a recycling process that can be used to help the rest of the factory decouple from grid energy. It may even be possible to run the process more aggressively to reduce the recycling operation carbon footprint to close to zero. IETF funding will help with largescale demonstrations.

INDUSTRY IMPACT

There is currently an anticipated demand of 107 kTe of carbon fibre, a volume which the supply chain is already struggling to deliver, even before it is anticipated to grow to 169 kTe by 2026. Companies are already struggling to source virgin carbon fibre due to manufacturing shortages and supply chain bottle necks, which have driven up the price of carbon fibre by 25-30% over the last few months. Increased demand from the hydrogen sector alone is expected to reach 100 kTe by 2030. This rapid increase in demand is driven by growth in the renewables sector, from pressure vessels for hydrogen storage to gas diffusion membranes and bipolar plates in fuel cells. Gen 2 Carbon believes that recycling carbon fibre will be key to meeting the growth in demand, focusing on short carbon fibre applications, achieved partly by recycling end-of-life wind turbine blades. They estimate that by 2030, up to 12 – 18 kTe of carbon fibre could be recovered from recycling blades and pressure vessel waste. This would be more than enough to satisfy the anticipated demand of 9 kTe for carbon fibre nonwovens. Virgin fibre should be reserved for high tensile requirements, whereas recycled carbon fibre can satisfy demands in all applications where short, discontinuous fibres are used today. Recycled carbon fibre products are viable replacements for aluminium, GFRP and CFRP materials in applications such as automotive exteriors and interiors, aircraft interiors, electronic casings and shell structures. They recognise that this will require a change in mindset but assert that it will help to reduce material shortages, costs and environmental impacts in the long-term.

FUTURE CHALLENGES

The immediate challenge for Gen 2 Carbon is securing the funding to support and accelerate expansion. They would also like to fully understand and assess the carbon footprint of different processes. Looking ahead, there would be significant benefit, if not a requirement, for the creation of specific standards for grades of virgin and recycled carbon fibre. While it is easy to source grades for aluminium and steel products, there are very few standards for fibre products – most existing standards are for specific tests. Although recycled carbon fibre has huge flexibility in application, the lack of industry standards can complicate manufacturing, as different customers can have a variety of requests. By establishing standards, the industry would be able to make products more accessible, while assuring customers on the quality of their recycled carbon fibres. This would allow customers to readily substitute products and move from specialty to commodity type applications. However, Gen 2 Carbon also recognises that standardisation may be complicated due to difficulties qualifying the use, performance and cost of different materials.

There is also a lack of infrastructure to disassemble blades, with the current recycling industry being too small to deal with the amount of waste generated. Gen2 Carbon believes that providing recycled carbon fibres with widely accepted industry qualifications will help to provide the business case to scale up current recycling facilities. By establishing the recycling industry near locations of high-volume waste generations, this could pave the way for developing the infrastructure to dismantle and transport blades.

11.4 ROSEHILL POLYMERS

Rosehill Polymers was established in 1988 and originally focused on Polyurethane manufacturing, before developing a process for manufacturing products from recycled tyre rubber. These first products initially ranged from playground floor tiles to level crossing panels within the rail sector. This provided the company with the experience to move onto bigger projects in the rail sector, leading them to become one of the biggest manufacturers of rail level crossings globally over the last 15 – 20 years.

Their position as a top UK manufacturer allowed them to progress into other industries such as oil and gas, highways, security, as well as more recently developing a modular road system for the smart motorways network.

For well over two decades, Rosehill has successfully challenged established products and processes in a wide range of industries and applications. Developing products for the offshore sectors initially led to pipeline coatings, thermal insulations and cable protections for the O&G industry. However, as the UK accelerates the installation of one of the largest offshore wind industries in the world, Rosehill recognised the opportunity to enter another new sector.

GROWTH AND FUTURE EXPANSION

Rosehill Polymers currently has approximately 100 employees across their five core business units specialising in the development and manufacture of coatings, adhesives, elastomers and moulded rubber products. They offer services to global customers in critical and national infrastructure with rail and highway solutions, athletics tracks with Sports and Safer surfacing, protection of buildings and people with UK Security Services rated security products and subsea critical pipeline / cable protection for the Offshore O&G industry.

They have identified the circular economy as an avenue to recycle secondary materials, reducing the need for high volumes of virgin materials during manufacture of new components and products. As many of their competitors deal with small consumer products, they are aiming to manufacture large scale products where engineering is the key to success.

To get a foothold in the renewables sector, they have been investigating various opportunities for possible collaborations or partnerships.

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As the cable protection systems required in the offshore wind industry are different from those used in the O&G industry, they are aiming to create a similar validated product history across new sectors. They are currently in discussions with the Net Zero Technology Centre on plans for O&G asset and wind turbine decommissioning.

ENVIRONMENTAL IMPACT

Rosehill Polymer uses cold curing, which results in minimal energy use in the manufacturing process. They also make use of materials that are high abrasion resistant, which help to increase the product's operational lifespan.

Their cable protection systems consist of 92 – 96 % recycled materials, with the remainder being 4 – 8% virgin resin, binding the material together. This diverts significant quantities of material from landfill or incinerators as well as substantially reducing the demand on virgin materials for manufacture. One study has shown that for every 1,000 kg of end-of-life tyres recycled, approximately 750 kg of carbon is saved from entering the environment by designing out virgin, carbon rich materials.

Rosehill have several renewable concepts which include their rubber shock pads, which would be developed for the dismantling of O&G / wind farm assets, without causing environmental concerns from leaked oil or the build-up of sand. These pads remove the need for considerable volumes of aggregate during the decommissioning process and they can be used repeatedly for different projects. They are also transportable, so they can be situated at different sites.

INDUSTRY IMPACT

Rosehill Polymers are confident that their recycled cable protection materials will be up to 50% cheaper than the standard polyurethane products currently utilised. They have begun investigating engineering solutions for dynamic cable protection, which could be a great opportunity to drive down the cost of floating offshore wind deployment.

FUTURE CHALLENGES

Currently, the greatest challenge for Rosehill Polymers is finding a way to break into the marketplace. Although they have the necessary skillset to provide products for the renewables industry, they do not yet have the market knowledge and experience to make the best use of it.

They are hoping to engage with collaboration partners to help identify commercially viable opportunities and understand any necessary areas for product development. Originally there was a focus on selling to operators, but they are now looking towards tier 1 contractors. Consideration has also been given to working with other existing manufacturers in the sector.

11.5 CEDECO

Cedeco was founded in 2014 and initially focused on the design of maritime vessels. This evolved in 2018 when they responded to a Scottish Power Renewables Innovation Challenge to find an alternative solution to the need for a grouted connection when installing jacket foundations for offshore wind turbines.

The team of two have been working on a number of grant funded projects with Kent (Atkins) since 2020 to develop their solution and in 2022 they were selected for the Net Zero Technology Centre's TechX Clean Energy Accelerator programme. The accelerator received over 200 applications, and Cedeco were one of the 5% of successful applicants enrolled in the intensive 15-week programme. The programme provided £100,000 grant funding, business acceleration support and access to major operators to help with customer validation. The programme is designed to support early-stage technology companies develop and assist with pitching for investment and field trials.

GROWTH AND FUTURE EXPANSION

They are developing a technology roadmap with support from industry peers and mentors and plan to start pitching for investment from June 2022. The company's aim is to develop the technology in collaboration with industry, creating a business model focused on licencing the Intellectual Property.

They hope to double the size of the team in the next year with the recruitment of a Product Development Lead and another member of the delivery team. They will also travel to Taiwan, as part of the delegation with Innovate UK, for the innovation trade mission to broaden their understanding of different geographical requirements and how the design can be adapted to deal with varying levels of seismic activity.

ENVIRONMENTAL IMPACT

As the design progresses and the value proposition is developed, the true impact of the product will be fully realised. However, early estimates suggest that the alternative solution to grout could provide up to 40% carbon emissions reduction. The removal of the grout eliminates the use of O grade aggregates and if the new system can utilise recycled materials, even greater carbon savings can be achieved. Additionally, the system would significantly reduce the amount of time required for large vessel operations and this would also substantially reduce vessel emissions.

INDUSTRY IMPACT

The potential cost savings for the industry have been estimated at up to 50 days reduction in installation time, which is the equivalent of up to £14 million savings in installation costs over 100 turbines.

FUTURE CHALLENGES

Industry is asking for solutions but are reluctant to fund innovation, preferring technologies to have reached TRL 6 for example, before being considered for investment.

11.6 2NDWIND

2ndWind Ltd. is a purpose-driven start-up founded in February 2021 with the mission to investigate feasibility of alternative uses for end-of-life wind turbine blades. To reduce the impact of large quantities of blade waste material expected with decommissioning, 2ndWind's vision is to use the blades with minimal re-engineering as assets for innovative new products and significantly reduce the number of blades requiring terminal disposal.

2ndWind is working with the University of Strathclyde and Glasgow Caledonian University to assess the feasibility of concepts for how blades may be productively repurposed. The envisaged applications for the products, if realised at scale, will help address some of the most pressing environmental issues facing the offshore wind industry. Positive outcomes from either of the current studies will be followed by detailed economic research to quantify market potential and determine whether there is a viable business model.

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LIST OF FIGURES

LIST OF TABLES

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