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An integrated geospatial approach for repurposing wind turbine blades

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ABSTRACT

The End-of-Life (EOL) stage of the first commercial wind farms is fast approaching and uncertainty remains in how to deal with their non-biodegradable Fibre Reinforced Polymer (FRP) composite wind turbine blades. Repurposing options could potentially delay large volumes of material entering unsustainable waste streams such as landfill or incineration and contribute to the circular economy. To plan waste management methods as well as inform the collective team of policy makers, decision makers and local governments, it is essential to understand and assess the geographical variability in the quantity of potential FRP composite blade waste material. Decisions regarding EOL blades are complex due to the varying numbers of blades and diversity in models, therefore it is essential that decommissioning plans are tailored for each location. This research introduces an innovative spatiotemporal approach to investigate the magnitude of the problem and quantify blade waste material associated with the EOL stage of wind turbine blades using the island of Ireland case study. The technical and spatiotemporal variability is assessed through an integrated Geographical Information Science (GIS) framework and online dashboard for decision-making. The findings indicate that for the island of Ireland approximately 53,000 tonnes of composite material will reach the EOL stage by 2040 with highest material densities located in the west and southwest of the island. The integrated GIS approach provides important information on blade type and model to assist decision-making on the design of repurposing strategies for FRP composite blades and provides an exemplar for other countries.

1. Introduction

The demand for renewable energy sources such as wind energy has increased with the urgent need to tackle global issues including climate change due to greenhouse gas emissions and energy security (Cherrington et al., 2012). Wind energy has become an important renewable energy source worldwide with the global installed capacity now reaching over 651 GW (GWEC, 2020), and is expected to double in use between 2019 and 2029 (Richard, 2020). With increasing demand to produce more energy, over the three decades from 1980 to 2009 wind turbine rotor diameters increased eightfold (Larsen, 2009). As wind turbine blades grow in both size and number, the amount of material required to engineer these large aerodynamic structures also increases. Around 80–85% of a wind turbine is made from metals which already have established recycling capabilities including the tower (often made from steel) and components inside the nacelle (predominantly steel, copper and aluminium). The blades however, are composed of Fibre-Reinforced Polymer (FRP) composite materials, which are more challenging to recycle (Psomopoulos et al., 2019). A typical wind turbine blade design involves a hollow aerodynamic profile comprised of two outer shells, bonded together using adhesives and supported by one or more load-carrying shear webs (Jensen and Branner, 2013). A wind turbine blade is composed of around 60% reinforced fibres (typically glass), 23% thermosetting polymer resins and adhesives, 9% core materials such as balsa wood or thermoplastic polymer foams and 8% metals including copper and steel (Fingersh et al., 2006). While modern wind turbine blade designs are predominantly glass FRP (GFRP) composites, carbon FRP (CFRP) is increasingly being used in sections of larger blades to increase stiffness and reduce the weight. The blade structure and material composition is proprietary information of the manufacturer and depends on the specific design parameters for that blade as well as the production year (Beauson and Brøndsted, 2016).

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A wind turbine has a design life of approximately 20 years and therefore many of the initial installations from the first commercial wind farms are fast approaching their decommissioning stage (Beauson and Brøndsted, 2016; Liu and Barlow, 2017). In addition, wind farm repowering is leading to wind turbines being taken down prior to their 20 year design life. This is creating a rising environmental concern due to the potentially large volumes of waste from the composite blades, which will need to be managed (Liu and Barlow, 2016). Liu and Barlow (2017) estimate that by 2050 there will be a cumulative total of around 43 million tonnes of blade waste globally and there will be around 2 million tonnes per year by 2050. This cumulative estimate agrees with Bank et al. (2018a) which was obtained using the future "moderate scenario growth" wind power estimates from the Global Wind Energy Council (GWEC, 2016). If the GWEC "advanced scenario growth" estimate is used the global cumulative total by 2050 will be about 60 million tonnes. This End-of-Life (EOL) stage of wind turbines has not been considered a problem or priority until recently and as a result has often been excluded from environmental management and Life Cycle Assessment (LCA) studies, leading to a lack of research and practical experience into the issues associated with the removal of the blades (Ortegon et al., 2013). A lack of allocated responsibility associated with dealing with the waste from rotor blades results in an exacerbation of the problem (Sultan and Mativenga, 2019).

While there is increasing awareness of the issue of EOL blades, there is still uncertainty about potential waste quantities. There is risk of a rapid accumulation of EOL blades, which will prove difficult to address, without advanced planning and preparation (Andersen et al., 2016). Liu and Barlow (2017) recognise the need to accurately predict waste quantities to help policy makers, governments and the manufacturing industry to prioritise waste reduction and minimise environmental impacts. A limited number of studies has attempted to conduct such research. Work by, Albers et al. (2009) suggests an approximate estimation of 10 kg of blade material per 1 kW installed power (10 t/MW). Using this method Albers predicts that there will be more than 200,000 tonnes of blade material worldwide in 2034 with approximately 25,000 tonnes of this material coming from Germany. Andersen et al. (2014) adopts Albers et al. (2009) blade model of 10 t/MW and concludes that globally composite material will increase to approximately 800,000 tonnes per year by 2050. Another study by Arias (2016) investigates material quantities for decommissioned wind turbines in the United States (US). This study determines blade weights for the top 11 wind capacity-rated states and then calculates an average of 11.3 t/MW (9.57 t/MW of composite material) for the remaining 39 states. Liu and Barlow (2017) highlight the need to take into account the development in blade materials and manufacturing techniques allowing for larger blades, and account for more accurate predictions by adopting a model of 8–13.4 t/MW. Their study also considers figures for the geographical variation in waste for the four major wind energy markets; China, US, Europe and the rest of the world.

The aim of this study is to introduce an innovative spatiotemporal approach through an integrated Geographical Information Science (GIS) framework and online dashboard approach to investigate the magnitude of the problem and quantify blade waste materials associated with the EOL stage of wind turbines to assist decision-making on the designing of repurposing strategies. The novel spatiotemporal GIS approach using an All-Ireland wind farm database for the island of Ireland case study, provides an exemplar for other countries to assist decision-making for circular economy repurposing options of FRP composite blades.

Present options for disposal of EOL blades include landfill, incineration and co-processing, in cement kilns (Larsen, 2009). Landfill is by far the most used globally, followed by incineration (with or without energy recovery). Co-processing in a cement kiln is being attempted at only one location in Europe (Nagle et al., 2020). To ensure wind energy remains as sustainable as possible, EOL options need to be assessed with reference to their position in the European Waste Hierarchy (Council Directive, 2008). Management options for composite FRP wind turbine blades are positioned in terms of sustainability, waste prevention is placed at the top and disposal methods such as landfill and incineration are ranked at the lowest tier (Fig. 1). Despite landfill being environmentally unpalatable, currently it is the most common disposal option for decommissioned wind turbine blades. In the US in one recent, well-publicised case around 1,000 decommissioned wind turbine blades have already been cut, stacked and buried in a site in Casper, Wyoming (Martin, 2020; Padraig, 2020). Landfill options are prohibited in some countries including Germany and the Netherlands and is unsuitable for space-constrained countries such as Ireland where landmass and availability of landfill space are more limited within a long-term perspective (; Ramirez-Tejeda et al., 2017).

Secondary applications such as the reuse, repurposing and recycling of blades, involve the flow of material into another product. While these management options delay the material entering waste streams, they still require disposal methods or a "third-life" application in the future (Gentry et al., 2020). Several recycling options have been proposed including mechanical, thermal and chemical treatments. Mechanical recycling involves cutting, shredding or grinding the material into smaller pieces that can be used as a replacement aggregate in concrete (Yazdanbakhsh et al., 2018a, 2018b). Thermal recycling methods such as Pyrolysis and Fluidised Bed Combustion (FBC) require the use of high temperatures to recover the resins, reinforced fibres and heat energy (Pickering, 2006). Chemical recycling such as Solvolysis can be used to recover the fibres from the resins using solvent mixtures (Job et al., 2016; Mattsson et al., 2020). The process of recycling is complex due to the mix of materials and the varying nature of composites with few standard procedures for their fabrication. Co-processing is another recycling method which involves the mixing of shredded blades with waste to use as a raw material substitution in cement kilns. This method is already used in Germany but may have potential viability in countries like Ireland in the future, however current suitable facilities are scarce (Nagle et al., 2020). Blades with possible resale value may also be refurbished for trade in the second-hand wind turbine market, however this is subject to turbine conditions (Sakellariou, 2018).

This research forms part of a multidisciplinary onshore wind project known as Re-Wind ((Re-Wind, 2020) which aims to explore sustainable repurposing options for decommissioned wind turbine blades in engineering and industrial applications. The design of circular economy strategies for EOL blades, could provide an attractive solution, turning waste into a resource, while delaying unsustainable disposal methods such as landfill or incineration. The repurposing of blades maintains the value of material for longer, while also replacing materials from new extractions, making it more favourable in terms of sustainability in the waste hierarchy (Leahy, 2020). Furthermore, this move towards a circular economy can help address the UN Sustainable Development Goals (SDGs) such as Goal 12 which is aimed at "responsible consumption and production" (Ratner et al., 2020). Some innovative repurposing ideas include the application of blades for affordable housing (Bank et al., 2018a), pedestrian bridges (Suhail et al., 2019; André et al., 2020), power transmission lines (Alshannaq et al., 2019), amongst others (Bank et al., 2018b). Previous projects have also investigated the use of blades for street furniture, children's playparks, bus shelters, sound barriers and bicycle shelters (Bergsma, 2007; Eilers, 2020; Jensen and Skelton, 2018; Miljøskærm, 2020). For successful planning and management of circular economy solutions it is important to not only quantify the availability of materials but also understand where it is coming from, enabling it to be dealt with locally and prevent it being transported large distances which may be costly and contribute to considerable CO_2 emissions (Leahy, 2020). It is critical for the quality and remaining mechanical properties to be fully evaluated for the blades to be reused in structural applications (André et al., 2020).

The EOL stage of wind turbine blades poses many challenges and requires significant, advanced planning with many decisions being heavily geographical in nature. Due to the complexity of the problem, achieving novel repurposing applications for decommissioned wind

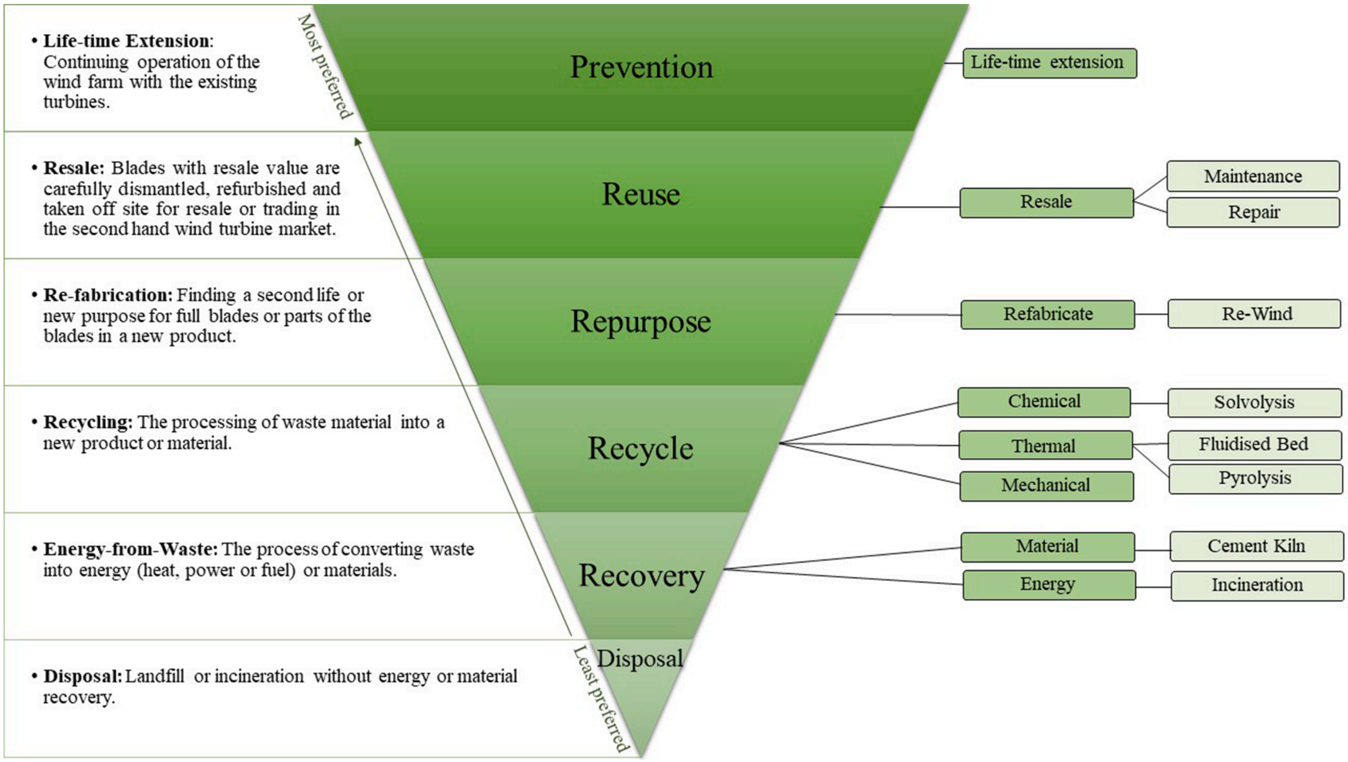

Fig. 1. Waste management options for composite materials in relation to their position on the waste hierarchy (Adapted from Ierides et al., 2018).

turbine blades has led to a number of constraints, many of which are spatially dependant. The exploitation of a GIS-based framework and geospatial protocols, and an up-to-date spatial database can assist in the designing of location-specific repurposing strategies by providing vital decision support through their ability to manage, store, analyse and map geographical information (Pokharel, 2000). To date there have been few research studies that have considered the benefits of using GIS for the planning of EOL wind farms. Sacchi et al. (2019) developed a wind turbine life cycle inventory for Denmark using GIS and taking into account the technical, temporal and geographical parameters. Serri et al. (2018) used GIS to investigate the geographical distribution of wind farm installations expecting to reach EOL by 2020 with the aim of developing potential repowering scenarios. While both these studies consider the use of GIS for the EOL of wind farms, neither of them account for the potential waste quantities. Sultan et al. (2018) consider the importance of modelling the geographic distribution of waste from EOL blades by using a mathematical model and centre-of-gravity method to identify potential sites for recycling. The importance of knowledge of the geographical distribution of wind turbine waste for onshore and offshore wind farms was highlighted in a recent study by Lichtenegger et al. (2020) which looked at a region level for Europe up to 2050. However, there is a lack of national studies, which are essential when developing locally specific repurposing strategies (Andersen et al., 2016).

In order to investigate the feasibility of the repurposing options and tailor designs for site-specific applications, this research showcases an approach to accurately quantify the availability of blade material and assess the technical and spatiotemporal variability in wind farm characteristics. Decisions regarding EOL blades are complex resulting from the quantity of blades, diversity of models and range of wind farm locations. Decommission plans therefore need to be tailored for each farm (Topham et al., 2019).The objectives of the current research are twofold: 1) to prove a more accurate and flexible GIS approach including the production of an online dashboard for predicting blade waste material including information on different blade models and sizes; and 2) to investigate the use of a Kernel Density Estimator (KDE) to identify high density locations of blade waste material to facilitate the allocation of resources for repurposing applications.

2. Methods and data

The methods in this study were developed using a GIS-based framework to provide important information to identify, quantify and characterise wind turbine blade material resources and their geographical distributions. The dataset in this research provides an updated and supplemented version of a database, obtained from TheWindPower (TheWindPower, 2018). This database provided information on wind farm locations represented as point data with attribute data including manufacturing details, developers and commission dates. These data were cross-referenced, corrected, where necessary, and updated using other available databases (IWEA, 2020; RenewableUK, 2020; SEAI, 2020; Wood Mackenzie, 2019). The resulting database was enhanced further through the collection of blade information including exact weights, lengths, blade details and materials (GFRP or CFRP) from published manufacturer turbine technical specifications. This has resulted in a comprehensive and most up-to-date database for onshore wind in Ireland which enables the prediction of decommission dates and waste material quantities.

2.1. Decommission dates

The decommission stage of wind farms in Ireland was divided into four decommission intervals, up to 2024, 2025–2029, 2030–2034 and 2035–2039 to allow the geographical and temporal variation to be assessed in more detail. Using the Re-Wind database (Re-Wind, 2020)), the decommission dates were predicted based on an expected service life of 20 years. A few of the earlier wind farm installations have experienced a life-time extension and repowering exercise and therefore these decommission dates were manually updated specific to the wind farm plans.

2.2. Waste predictions

To calculate precise estimations for blade material for this research, the blade weight (tonnes) was used as reported in the turbine manufacturing specifications. To achieve blade waste values per turbine the actual blade weights were multiplied by three because all modern wind turbines contain three rotor blades. To account for missing information on blade weights due to manufacture non-disclosure and defunct manufacturers of older blade models, the remaining weights were estimated. The data were analysed to investigate the relationship between blade weights as a function of blade length, rotor diameter and rated power. A linear relationship between the blade weight and the turbine rated power presented the strongest statistical relationship (Fig. 2; R^2 value = 0.95) and was selected to estimate the remaining blade masses. The average blade mass per unit rated power was calculated at 10.33 t/MW for the Irish case study (Fig. 2). The weight values (per 3 blades) were then multiplied by the number of turbines in each farm to obtain values per wind farm. Finally, the annual blade waste was obtained by summing the material quantities per expected decommission year.

2.3. Online dashboard

The key data from the Re-Wind database were presented in an interactive geospatial dashboard platform (ArcGIS online Dashboard) allowing data to be visualised in an intuitive way for efficient decision-making. The dashboard was designed to present the key data in separate elements including maps, charts, gauges and indicators, all linked together to provide context for the decision-making process. An interactive Web Map was first created on ArcGIS Online using the Re-Wind database. This map was configured to display the precise locations of the wind farms using graduated symbology to represent the number of turbines in each wind farm. A pop-up box was also created to present additional attribute information associated with each wind farm. This map provided the keynote for the creation of the remaining elements in the dashboard.

A pie chart was added to the dashboard with each segment proportional to the count of each turbine model type. Turbines that represented less than 1% were grouped together to prevent the chart becoming cluttered due to the diversity in turbine models. A serial chart was produced to show the estimated quantity of blade material per expected decommission year, while an indicator was used to display the sum of blade material from wind farms. A gauge was also used to display the count of wind turbines in the current map view out of the overall number of turbines in Ireland. Following this, a series of actions were set to link the different elements together, enabling the data to be filtered and adjust the map extent corresponding with the data in view (and vice versa). The dashboard is currently in development and calculations are based on data available at the time of creation. These data are updated regularly when additional information is added to the wind farm database.

2.4. Kernel density estimation (KDE) analysis

A number of spatial tools are available that can be used to identify patterns, relationships or distributions of features including; cluster analysis, statistical hotspots and KDE. In a study by Chainey et al. (2008) the KDE approach exceeded the cluster analysis and statistical hotspot mapping in terms of accuracy and visual appeal. KDE is a measure used to calculate the density of points within a neighbourhood to identify hotspots (Chainey, 2013). KDE analysis involves placing a kernel or symmetrical surface over each point, giving a higher weight to nearby events than those further away, and then finally summing the surfaces to produce a density estimate (Anderson, 2009). The KDE approach was deemed appropriate to use in this study because the wind farm data are represented as point features and KDE enables the density to be weighted using a population field. This means that a wind farm with higher waste quantities is given greater weights than those with less waste and thus is more representative of reality. The KDE analysis in this study is based on a quartic kernel (Silverman, 1986) and the predicted density can be determined by Eq. (1);

$$Density(x,y) = \frac{1}{R^2}\sum_{i=1}^{n}\left[\frac{3}{\pi}y_i\left(1-\frac{d_i^2}{R^2}\right)^2\right] \quad (1)$$

Where $i = 1, \ldots, n$ are the input points. y is the population value of point i and R is the bandwidth (search radius). d_i is the distance between the point i, and the event location (x, y). The KDE requires two key parameters to be set; the cell size (resolution) and the bandwidth. The bandwidth is more important than the cell size because it determines the actual outcome of the kernel. A larger bandwidth increases the number of points to be included giving a more general output, while a smaller bandwidth accentuates clusters (Lloyd, 2010). When the kernel is not smoothed sufficiently it contains spurious features known as artefacts, however when the kernel is smoothed excessively it may lead to the loss of important features and therefore it is important to determine the right bandwidth value (Danese et al., 2008). A full analysis was carried out to

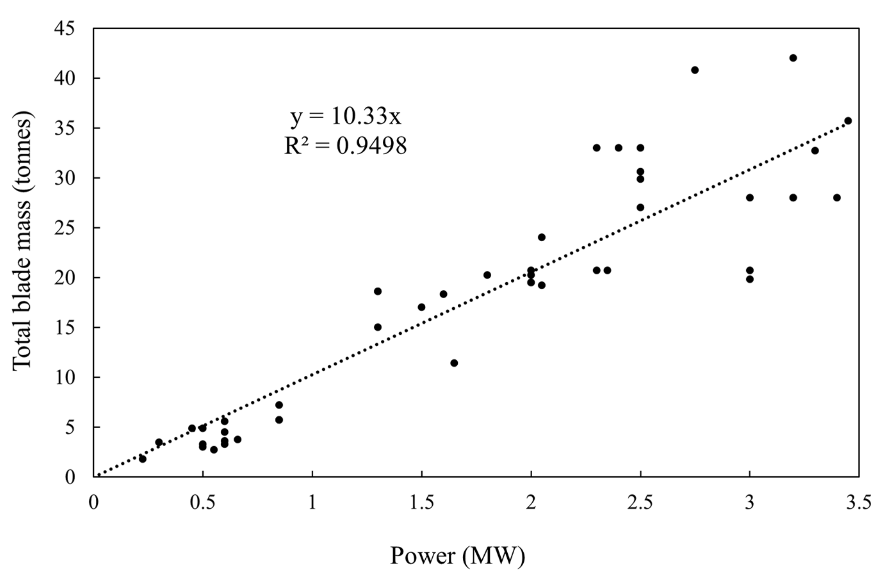

Fig. 2. Blade mass as a function of rated power for Irish wind farms.

test the different bandwidth and cell sizes to best represent the spatial distribution of wind turbine blade waste in Ireland. The Kernel Density (KD) maps were generated using a 12.5 km search radius, a cell size of 50 m and were weighted using the tonnes of blade material. A bandwidth of 12.5 km was considered the most suitable for the requirements of this study as it enabled the clusters of waste to be observed without excessively smoothing the data and losing the important wind farm locations. A cell size of 50 m was regarded as an appropriate parameter for this analysis because a higher resolution is not necessary for a national level case study area. Overall, the analysis of the study revealed that the cell size had less impact on the outcome of the KDE results. KD maps were then created using these selected parameters to pinpoint concentrations of blade material available throughout the four defined decommission time intervals.

3. Results

The findings from this research indicate an estimated 53,000 tonnes of blade material from onshore wind by 2040 (Fig. 3). The material composition is approximately 31,800 tonnes of GFRP, 12,200 tonnes of resin and adhesives, 4,800 tonnes of core material and 4,200 tonnes of metals. The blade material primarily begins to accumulate from around 2023 with an increase year on year, peaking in 2037 with approximately 9,000 tonnes of blade material (with composite materials accounting for around 7,500 tonnes). This peak in 2037 results from the large installed capacity of wind turbines in 2017 in addition with the newer turbines having a larger mass and dimensions. Some fluctuations in blade material are experienced each year between 2030 and 2039 resulting from changes in the wind energy market affecting the installed capacity.

The results of the study indicate that some wind farms in Ireland would have been expected to be decommissioned before 2020 and have exceeded their 20 year service life, with no known plans to remove or dismantle the turbines. This may be due to some wind farms in Ireland being granted consent to operate in perpetuity when the application was lodged over 20 years ago (Windemer, 2019). This means that if the turbines are still profitably operable the wind farm may continue to run beyond the expected life-time. Repowering or decommissioning the site may be avoided due to new planning applications associated with new work on the site.

Other farms expecting to decommission are also in the planning phase to repower their sites with newer turbines. Some repowered farms may have fewer turbines than the previous phase due to them being larger and more efficient thus producing more energy. Life-time extension of a wind farm is complex owing to the technical, economic and legal aspects (Ziegler et al., 2018). Liu and Barlow (2017) found that some manufacturers could potentially extend the life time up to 25 years but this is subject to the wind turbine condition. Life-time extension therefore introduces uncertainty into the forecasting of blade material availability, however only the timing, and not overall waste volume, will ultimately be affected. This highlights the need for communication and sharing of information within the wind industry.

The GIS online dashboard indicates that there will be an estimate of over 2,600 wind turbines expecting to decommission by 2040 on the island of Ireland (Fig. 4a). The dashboard created for use by the Re-Wind project presents the key information needed for decision-making in a way which can be easily understood by all. This information provides a reference point for the team to view and interact with the data. The user can interact with the map by zooming in and out to their chosen location and the dashboard elements will update according to the features in the current map extent (Fig. 4b). The user can also select and filter the data according to specific attributes. The central map will adjust to display relevant wind farms and the remaining elements will adjust to the updated selection (Fig. 4c and d). Using the multiple visualisations in one single screen the dashboard draws attention to the key issues associated with EOL blade waste and provides a way to share the same data with the team enabling everyone to be focused on the same goal.

An investigation of the database identified the most used turbine types and blade lengths in Ireland. This information is important to a repurposing design team such as Re-Wind to identify the size and types of blades close to EOL in order to tailor repurposing designs to certain blades. Applications such as a bridge or roof based on repurposed blades will have specific dimensions which will limit the number of blade models suitable for the particular repurposing option (Gentry et al., 2020). An assessment of different blade lengths in relation to the four decommission time intervals identified if certain blade characteristics were associated with different decommission intervals, to inform prioritisation of repurposing designs.

Ireland has approximately 8,000 FRP blades expecting to be decommissioned before 2040, with blade lengths ranging from 13.5 to 58.7 m. The majority of the known blade lengths fall in the range of 30–49 m (Fig. 5). During the first phase of decommissioning up to 2024, the majority of blades are less than 29 m with the smallest blade being

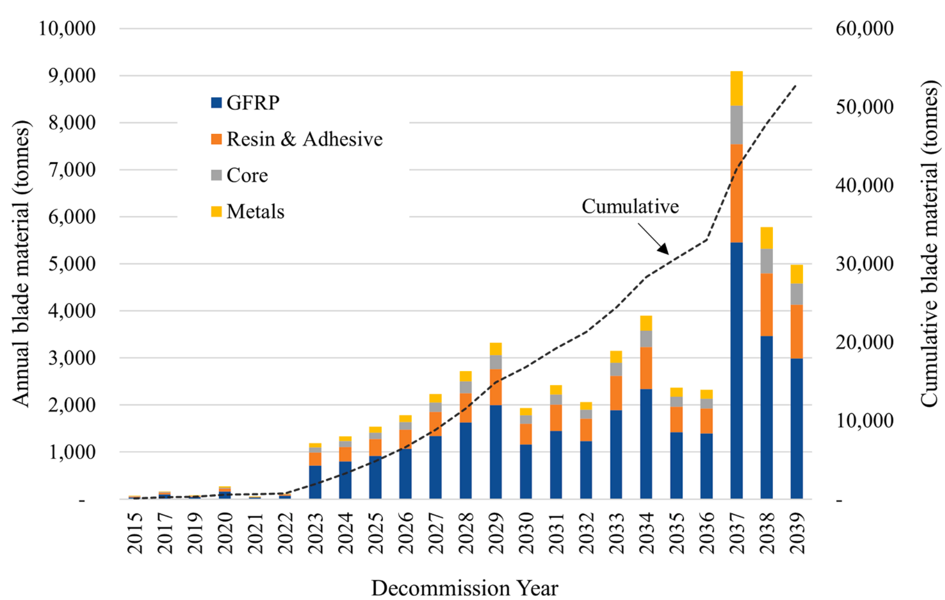

Fig. 3. Estimated cumulative and annual blade material quantities for onshore wind farms in Ireland up to 2039 (Re-Wind 2020 database). The material breakdown is shown for each year based on Fingersh et al., 2006.

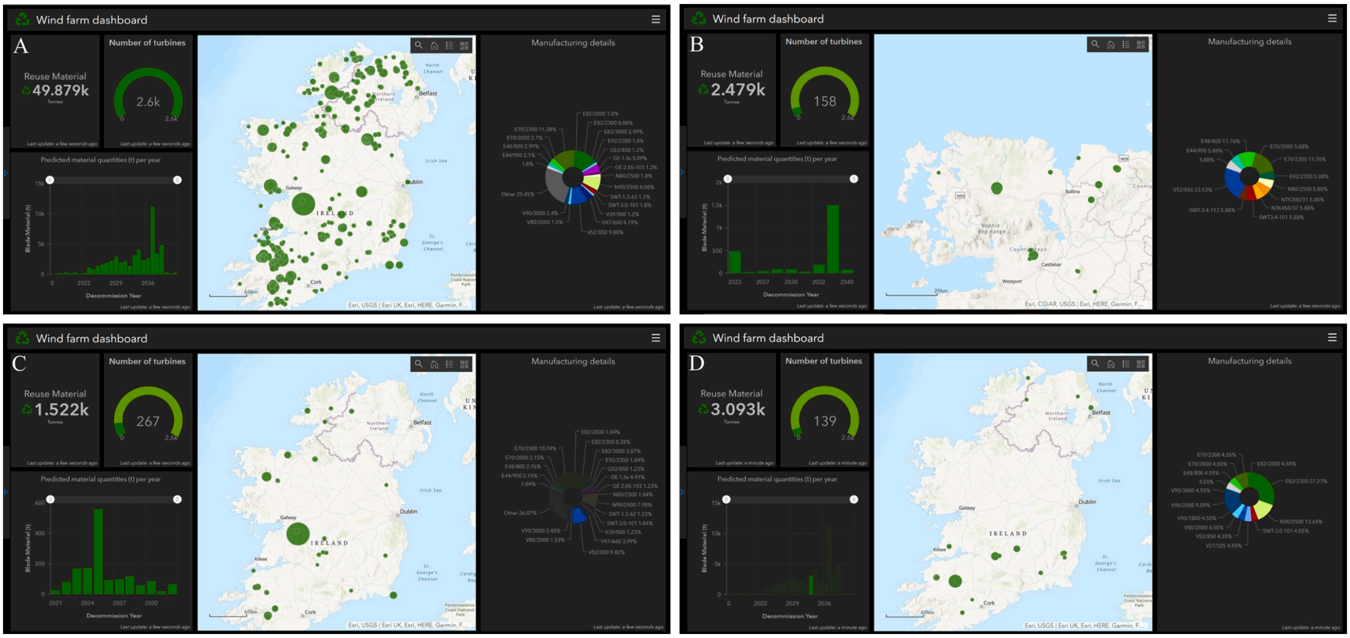

Fig. 4. Screen view showing how the interactive Re-Wind GIS online dashboard works (Re-Wind 2020 database). (a) shows an overview of all wind farms in Ireland. Here the amount of reuse material, turbines and manufacturing details are presented for the wind farms in the main interactive map. As you zoom in and out to specific locations these elements will all adjust as shown in (b). (c) shows the selection of a specific wind turbine model (V52/850), the interactive map adjusts to show the location of these farms and the other elements adjust accordingly. (d) shows the selection of a specific decommission year, the location of these farms and associated number of turbines, reuse material and turbine models.

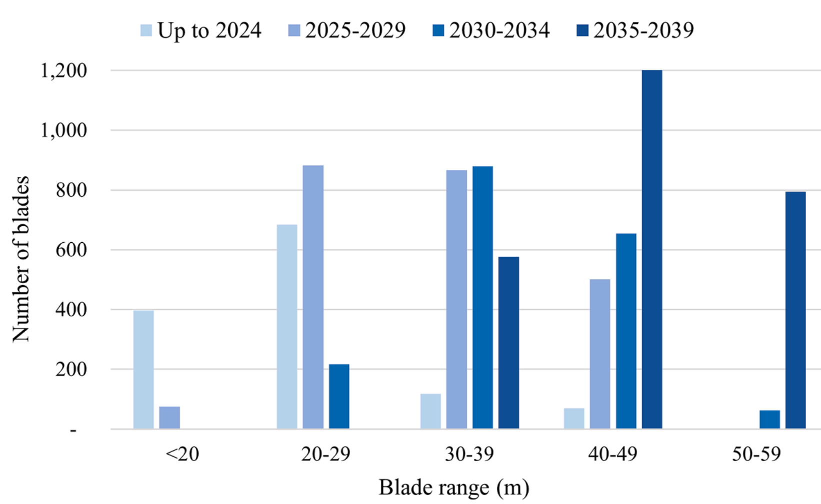

Fig. 5. Histogram showing the number of blades falling into each blade length category for the four defined decommission time intervals in Ireland (Re-Wind 2020 database).

13.5 m and none are above 50 m. The average blade length during this phase is 24.3 m. Between 2025–2029 the majority of the blades fall into the next range of blade sizes between 20 and 39 m with an average blade length of 31.3 m. From 2030–2034 the majority of the blades are between 30 and 49 m with no blades in the smallest range <20 m and an average blade length of 37.8 m. Finally from 2035 onwards the blades range in size from 30 to 58.7 m with no blades less than 29 m in length and an average length of 43.9 m. There is a clear trend that blades are increasing in size towards the later decommission intervals (Fig. 5). This is a result of the development in blade materials allowing longer blades for greater rotor swept areas and power capture.

The aerodynamic shape and structure of a rotor blade is carefully planned to ensure maximum efficiency. The design of the geometric profiles and aerofoil structures vary depending on the manufacturer and therefore it is important that repurposing strategies are tailored to different turbine varieties (Mishnaevsky et al., 2017). An analysis of overall turbine models in Ireland shows that the Nordex N90–2.5 MW turbine model is the most popular turbine in Ireland with approximately 11.3% of the market (Table 1). This is then closely followed by the Vestas V52–850 kW (10.2%) model and Enercon E70 2.0–2.3 MW models (10%). The remaining 30% represents the blades which have less than 2.5% of the installed capacity. The data show that a wide range of turbine models are installed in Ireland indicating that the repurposing solutions need to be versatile and widely applicable.

There are observed hotspots of material identified towards the northwest and southwest of the island with counties such as Kerry, Cork, Tyrone, Donegal and Tipperary expecting volumes between 4,100 – 6,900 tonnes by 2040 (Fig. 6). County Kerry is expected to have the largest material concentrations on the island with an estimated value of nearly 6,900 tonnes (12.9%) followed closely by Cork with an estimated

Table 1
Irish installed capacity by turbine model (top 10) for onshore wind farms.

	OEM	Model	Power (MW)	Installations (%)
1	Nordex	N90/2.5	2.5	11.3
2	Vestas	V52/850	0.85	10.2
3	Enercon	E70/2.0	2	10
		E70/2.3	2.3	
4	Enercon	E82/2.0 – E2	2	8.5
		E82/2.3 – E2	2.3	
		E82/2.35 – E4	2.35	
		E82/3.0 – E4	3	
5	Siemens	SWT-3.0–101	3	6.5
		SWT-3.2–101	3.2	
		SWT-3.4–101	3.4	
6	GE	GE 1.5 s/sle	1.5	6.1
7	Vestas	V90/1.8	1.8	4.3
		V90/2.0	2.0	
		V90/3.0	3.0	
8	Vestas	V47/660	0.66	4.2
9	GE	GE 2.5–103	2.5	4.2
		GE 2.75–103	2.75	
		GE 2.85–103	2.85	
		GE 3.2–103	3.2	
10	Siemens	SWT 2.3–82.5 / VS	2.3	3.7
The remaining 30% are a mix of different models <2.5% of the installed capacity in Ireland.				~30

value of around 6,400 tonnes (12%) by 2040. Concentrations of blade material diminish towards the east of the island where counties experience minimal to no blade waste. This information provides an important guide to local governments and councils to help plan and prepare for the possibly large volumes of non-biodegradable blade material. In addition, it provides locational evidence to focus preparations on areas which are expecting to have significant quantities of material and help come up with repurposing designs tailored to local needs. This information can aid decision makers involved in the decommission stage and planning of a circular economy approach as it can be used as a guide for finding suitable locations for start-up businesses and remanufacturing facilities.

KD maps show the spatial distributions of blade waste material and identify clustering of blade material for all wind farms decommissioning up to 2039 in Ireland (Fig. 7). The analysis shows that there are concentrations of material towards the west and southwest of the island. The highest densities of material are located approximately 18 km southeast of Killarney, 20 km west of Galway and around the Tipperary area. The majority of these high density areas have clusters of wind farms with high numbers of turbines. These high density areas are newer wind farms which have installed greater turbines with larger blades contributing to more blade material at the EOL stage. A large number of turbines does not necessarily result in high concentrations of waste, as shown by the large wind farm in county Galway with over 70 turbines in the area, but which does not appear to have a high density on the Kernel maps. Other concentrations of blade materials can also be seen north of Killarney, in Donegal and west of Northern Ireland (Fig. 7a).

In the first decommission interval up to 2024 the majority of the blade waste is encountered in the northwest of the island (Fig. 7b). While this map presents a high concentration of material in this phase the kernel values for density are much lower than in the other intervals (Fig. 7c–e). This is likely to be a result of a lower total number of wind farms and smaller turbines in place. The next decommission interval between 2025 and 2029 experiences high densities of blade material towards the southwest of Ireland with smaller densities surrounding (Fig. 7c). The results indicate that densities can also be seen towards the north of the island. During the decommission phase 2030–2034 the highest density of blade material lies in the southwest of the island (Fig. 7d). This map also presents a greater spread of material densities throughout the island with some hotspots towards the middle and south of the island as well as the northwest. Between 2035–2039 the majority of the blade material in Ireland is located towards the west of the island with the greatest concentration of blade material located west of Galway (Fig. 7e). The material hotspots are also spread throughout the island and can be seen in the northwest of the island. The KDE values are higher in this map showing that there is a greater concentration of blade material during this EOL interval in comparison to the other phases. The higher KD values in this map may result from the larger turbines installed as the wind industry matures in Ireland. The maps allow us to assess where the material will be available throughout the four phasesbased on five year intervals.

4. Discussion

Once the EOL stage has been reached for a wind farm there are two main options; (1) to repower the site (2) to decommission the site completely. Repowering the site involves dismantling the older existing wind turbines and replacing them with newer, larger and more efficient turbines, while reusing existing infrastructure (Martínez et al., 2018). The decommissioning of a wind farm involves the complete removal of the wind turbines and returning the site as close to its original state (Ortegon et al., 2013). For Ireland to reach its 70% renewable energy target by 2030 it cannot lose its capacity through decommissioning the farms, thus repowering the site is key to sustaining its wind energy capacity (IWEA, 2019). According to the SEAI (2017), repowering the wind farms both onshore and offshore in Ireland will contribute to 15 GW by 2050. Whether a wind farm is repowered or completely decommissioned, the existing turbines still need to be dismantled and materials need to be managed, therefore waste quantities and locations are necessary for the planning and removal of the blades.

The problem associated with the disposal of wind turbine blades at the EOL stage is imminent in Ireland and elsewhere across the world (Liu and Barlow, 2017). The EOL stage of wind turbines has received little attention and there still remains uncertainty about what will happen to the non-biodegradable blades once this stage is reached. Currently there are no government regulations or industry guidelines for the safe dismantling and responsible waste management associated with this stage (Ferdinand et al., 2019). In addition, landfill and incineration regulations in Europe are getting more stringent each year, and in some countries landfilling is already prohibited. In order to assess the potential options for EOL blades it is necessary to understand the extent of the problem as well as understand where and when the blade material will be coming offline.

Building a spatial database of where the ageing turbines are currently operating allows for an assessment of where and when the blades will be reaching EOL, facilitating planning and preparing of potential repurposing solutions. These results provide a reference and highlight the magnitude of the problem for decision makers as well as call for potential policies and guidelines to be drawn up to ensure it is dealt with in a sustainable way to prevent potential bottlenecks in waste disposal. With an expected 53,000 tonnes of FRP composite material from wind turbine blades by 2040 in Ireland (Fig. 3), the landfilling of these large composite blades is not only the least favourable option in the waste hierarchy in terms of sustainability but is also unsuitable due to the bulky nature of the blades causing them to have a high volume per tonne compared to conventional waste. Landfill disposal is also subject to tax tariffs and tipping fees in both the UK and Ireland, with rates of £91.35 per tonne (UK) and a government levy of €75 per tonne with an additional gate fee charged by the owner (~ €38) (HMRC, 2020; Nagle et al., 2020). While there are currently no bans for composite blades in landfill sites in Ireland, it must only be considered a last resort and even still, there are few landfill sites willing to accept blade waste. Furthermore blades must also be pre-treated if possible before landfill disposal to separate out any material that may be suitable for recycling or recovery. Therefore it is most likely that the waste contractor will assess this material to consider all options for recycling or recovery (including energy recovery) before sending it for disposal. In the event that there are no other outlets for this material, it can then be sent to a

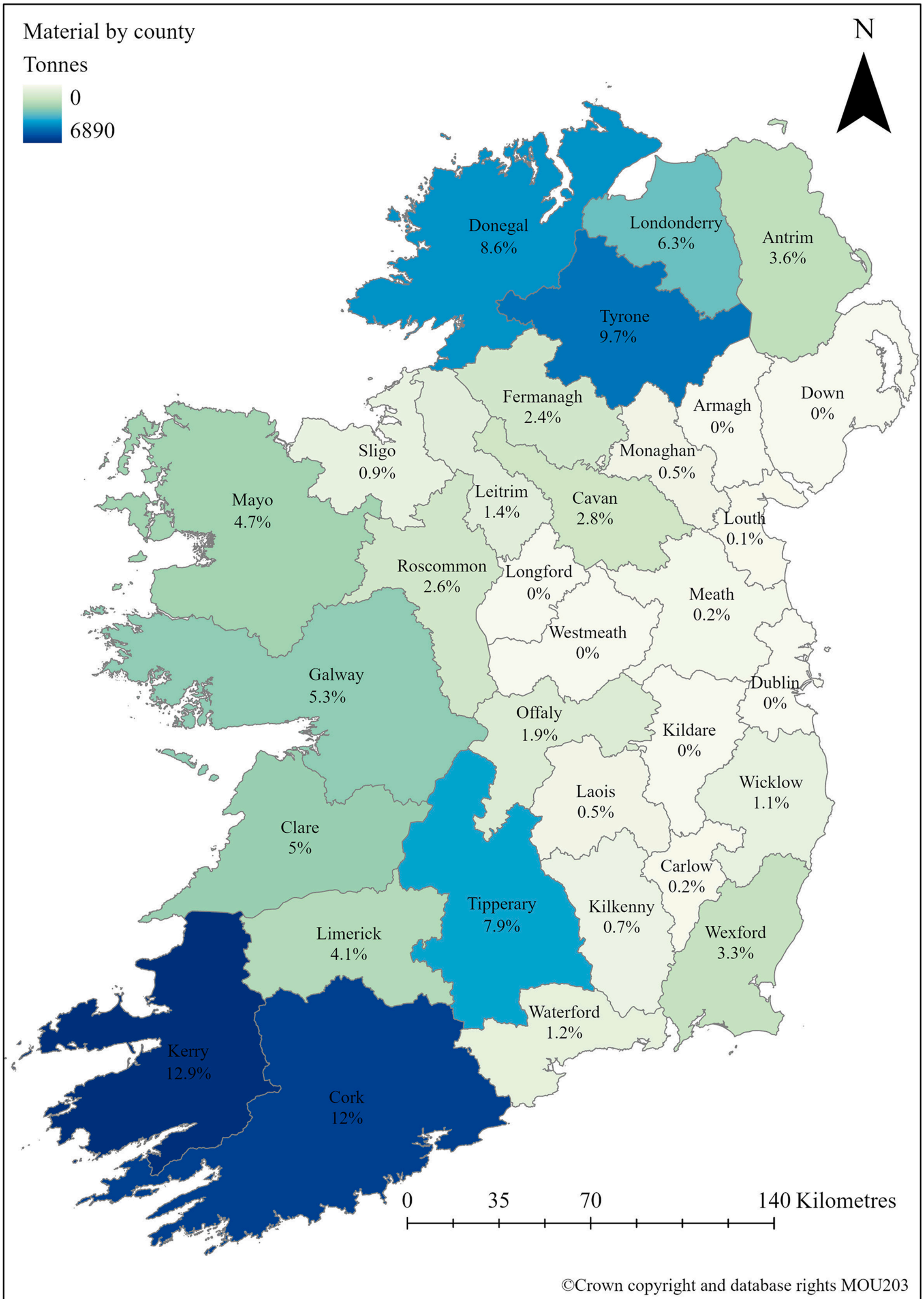

Fig. 6. County level forecast for blade material in Ireland (Re-Wind 2020 database). County boundaries are based on OSNI and OSI data. Reproduced from Land and Property Services data with the permission of the Controller of Her Majesty's Stationery Office, ©Crown copyright and database rights MOU203.

non-hazardous landfill without any further treatment. The results of this study emphasize the need to prioritise potential repurposing solutions with Ireland providing a good model and example for other countries worldwide.

These waste-to-resource scenarios provide a second life for the blade material while also reducing the demand for virgin materials. The feasibility of circular economy strategies for EOL blades is largely dependant on the availability of blade material. One of the key constraints hindering the development of a waste-to-resource strategy for EOL blades lies with the uncertainty and variability in long-term supply,

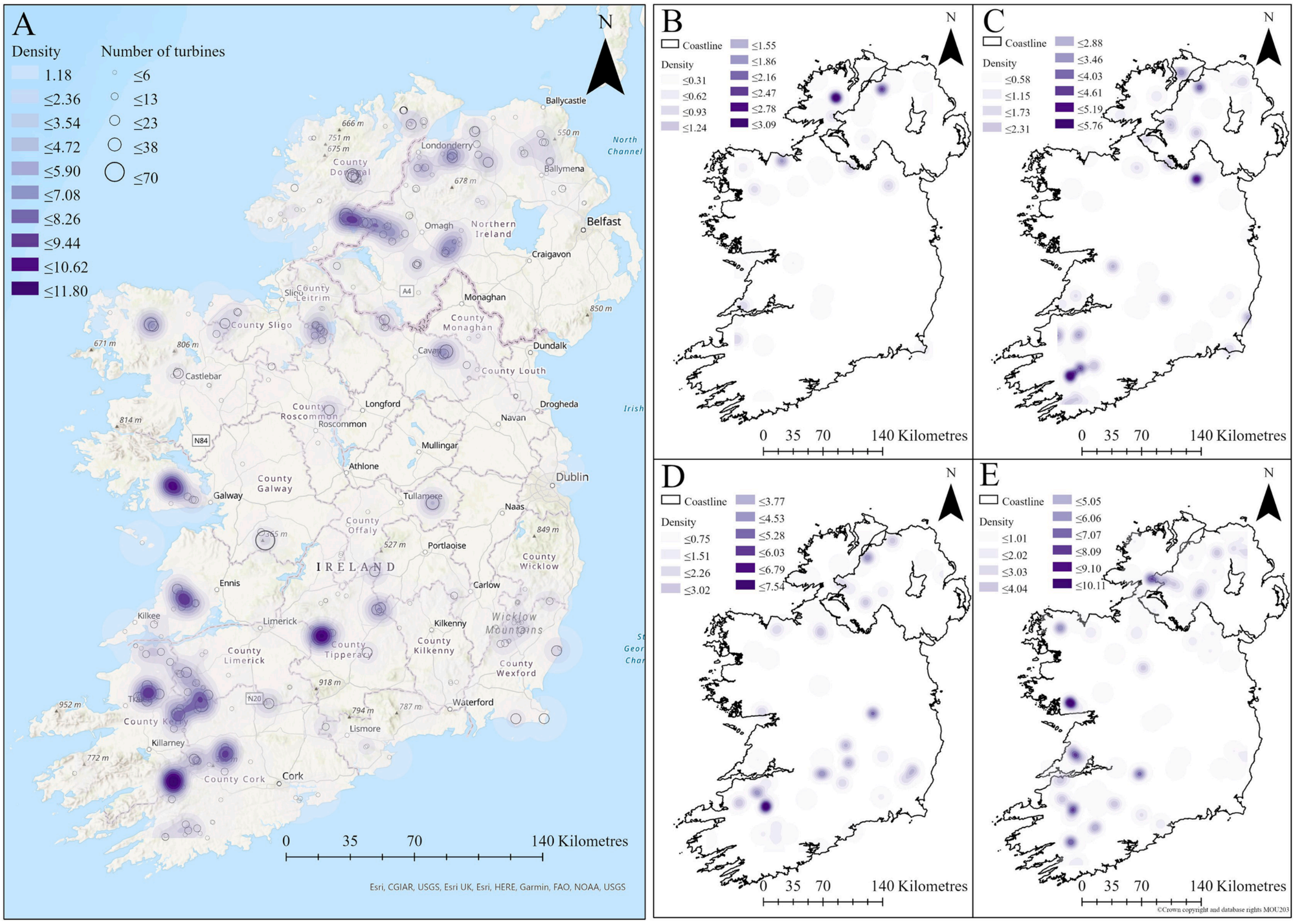

Fig. 7. Wind turbine blade material density maps for Ireland (Re-Wind 2020 database). (a) KDE map with number of wind turbines for all wind farms in Ireland decommissioning before 2040. Wind turbine density maps for the four defined decommission time intervals; Up to 2024 (b), 2025–2029 (c), 2030–2034 (d), 2035–2039 (e). Coastline is based on OSI and OSNI boundaries. Reproduced from Land and Property Services data with the permission of the Controller of Her Majesty's Stationery Office, ©Crown copyright and database rights MOU203.

material composition and quantities available. For circular economy scenarios to be developed it is necessary to quantify and identify the origins of the blade waste material, assess the different blade types and materials as well as gauge when a management plan will be needed (Jensen et al., 2020). These material flows and locations are essential for the viability of repurposing and recycling, and can help persuade stakeholders about potentially investing in this market (Psomopoulos et al., 2019).

In this study the wind farm locations are represented as point data with additional information stored in attributes. In GIS, different symbology can be used to represent and encode the different features at a location. Graduated symbology could have been used to represent the material quantities at each wind farm location however, often where separate events occur in close proximity can lead to the illusion of them overlapping (Lloyd, 2011). An example of this limitation can be seen in the results where graduated symbology was used to show the number of wind turbines in each wind farm (Fig. 7a). KDE mapping provides a way to visualise and summarise the data to enable patterns to be detected. Mapping the intensity estimation is a useful method to visually identify hotspots (Lloyd, 2011). The application of KDE highlights the areas which are expected to experience the highest densities of blade material in Ireland. The highest concentration of blade material is important to facilitate the allocation of resources available for the application in repurposing strategies. Through the generation of time and location, the KDE maps indicate where most impact is generated and can provide reference for policy makers and decision makers on what and where to prioritise. Understanding wind farm locations and the quantities of blade material allow for the repurposing scenarios to be tailored to local needs. The results also show that there is a wide range of turbine models and locations making it difficult to have one standard approach for dismantling and managing the turbines. This highlights that the plans and models for EOL blade repurposing need to be adaptable and widely applicable. According to the UBA, the dismantling costs for a wind turbine in Germany are estimated at €30,000–60,000 per MW and vary depending on the wind farm location, size and turbine model (Knight, 2020). Furthermore, for the blades to be repurposed it is likely that a remanufacturing facility will be required to modify and retrofit the blades. Many of the wind farms in Ireland are distributed in areas of higher elevation and remote locations which are often far from waste management facilities, presenting a challenge for the transportation of the blades. It is important to assess the existing facilities or find potential new amenities at an optimum distance from the wind farms (Andersen et al., 2016). All of the aforementioned problems are spatial in nature and therefore the use of GIS can assist in decision support.

The results of this research are essential to not only investigate the feasibility of repurposing but also assess the viability of industrial level recycling. The industrialisation of blade decommissioning will require a collaboration between multiple stakeholders across the wind industry. The dashboard, maps and figures presented in this study provide an innovative approach to present and visualise the data in a way that is understood by all participants. The methods used in this study are applicable to other geographic locations and also the offshore wind industry.

It is important to note that the waste prediction results in this study are based on blade material from wind farms at the EOL phase only. Blades may be replaced throughout a wind turbine's life span due to blade failures. Blade replacement accounts for approximately 1–3% of the wind turbine blades (Liu and Barlow, 2017). Blade replacement due to failure was not deducted from the overall calculation of the quantity of repurposing material. However, blades that have failed structurally and have been removed from the turbine should only be used for structural repurposing with extreme caution due to the uncertainty of the structural quality of failed blades or parts of failed blades.

Blades that have not failed prematurely and are decommissioned need to be checked for any repairs made to the blade during its service life. These repairs, which may be necessitated due to lightening strikes, leading edge erosion, trailing edge failure or other manufacturing related defects, must be assessed before they can be used for repurposing to determine if the prior damage makes them structurally vulnerable (Katnam et al., 2015). This may include destructive or non-destructive tests or full-structure proof tests on the repurposed structure. Likewise, any fatigue damage leading to material strength or stiffness degradation needs to be taken into account in the repurposing structural design (Post et al., 2008).

This paper presents time related data and is a prediction based on the data available at the time of analysis. These figures may change as data are updated and edited in the wind farm database. A limitation with waste prediction data is that it becomes obsolete almost as soon as it is produced (Jensen et al., 2020). As with all models and spatial analysis, the accuracy of the results strongly rely on the quality of the input data. All models are estimations and representations of reality and therefore error is inherent to some extent. Potential sources of error may enter the decision-making process from data acquisition, spatial analysis through to how the results are presented (Lunetta et al., 1991). Any uncertainties that enter through data acquisition will propagate into the final results. Often when comparing and cross-referencing information between the different databases there are discrepancies between some of the data. Communication and sharing of data within the wind industry and with researchers could further enhance the accuracy of the results, improve models and design better solutions for waste management. Kusiak (2016) highlights the benefits and need to develop protocols for sharing data in a secure way while maintaining confidentiality.

5. Conclusion

While the EOL is fast approaching for many wind farms in Ireland, it is clear that there are no definitive plans in place to address this EOL stage of the blades. This research addresses the magnitude of the unfolding problem associated with EOL blades in Ireland. The innovative approach included a collection of information on wind farms and blade manufacturing details into an integrated GIS framework. Within this spatial framework approach, material quantities were estimated using exact blade weights were possible, different blade types and numbers were assessed and material density maps created with an exemplar shown for the island of Ireland. Additionally, KDE maps were created to analyse the spatiotemporal hotspots of blade material locations throughout four selected decommission time intervals. The results of the spatial database and density maps indicate that approximately 53,000 tonnes of composite material will need to be managed by 2040 across the island of Ireland. The majority of this waste is located in hotspots towards the west and southwest of the island. County Kerry followed by Cork, Tyrone, Donegal and Tipperary experience the largest potential quantities of blade waste material. This information can provide a guide for policy makers, decision makers, the wind industry, local governments and councils to understand the extent of the problem and prepare waste management strategies. These results highlight a key challenge faced by the Irish wind industry resulting from the potentially large volumes of blade waste material. This meticulously sourced information can also aid in the designing and planning of repurposing strategies which can provide a circular economy solution by giving the blade material a second life thus delaying it entering waste streams. The quantification and spatiotemporal variability in blade waste material allows for advanced planning, ensuring that the stream of waste is handled in an environmentally sustainable way and enables it to be dealt with locally, preventing carbon intensive long distance transportation. The methods presented in this study could further be applied to a full Europe survey to investigate the problem of wind turbine blade waste. Future research could consider the inclusion of blade details such as the internal structure, detailed material properties and 3D models. In addition, the sharing of data with researchers in a controlled way offers the potential to facilitate more accurate results and better decision-making.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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