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Review article

End-of-life wind turbine blades and paths to a circular economy

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ABSTRACT

A structured literature review is used to identify barriers to the recommended methods of processing end-of-life wind turbine blades. The Waste Management Hierarchy recommends firstly avoidance, then repurposing, recycling, energy recovery and lastly, disposal. The review finds that most recent research articles are concerned with recycling, despite its position in third place in the Hierarchy. The review also identifies the following barriers to the first, second and third most recommended processes: misalignment of financial rewards for blade manufacturers making more durable blades; lack of information about blades which could help repurposing and recycling; and lack of financial incentives for any of the top three methods. Based on these findings the following solutions are proposed: alternative payment structures for blade ownership incentivising blade quality and longevity; an information exchange to facilitate the second hand market, repurposing and recycling; and the widespread use of compliance bonds to provide a financial incentive for repurposing and recycling.

Contents

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Abbreviations

9R	Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle & Recover
ASCE	American Society of Civil Engineers
CEBMs	circular economy business models
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFRP	carbon fibre reinforced polymer
DECC	Department of Energy and Climate Change
EPA	Environmental Protection Agency
FRP	fibre reinforced polymer
GE	General Electric
GFRP	glass fibre reinforced polymer
GW	gigawatt
IDIS	internal dismantling information system
IEA	International Energy Agency
IOP	Institute of Physics
MWh	megawatt hours
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PVC	polyvinyl chloride
SDG	Sustainable Development Goal
SMCRA	Surface Mining Control and Reclamation Act
SWOT	strength, weakness, opportunity, threat
TWh	terawatt hour
WMH	waste management hierarchy

1. Introduction

The seventh Sustainable Development Goal of the UN aims to provide affordable and clean energy [1]. While wind power has made progress in becoming cheaper, there is still a hurdle to be overcome in terms of its aim to be clean. It is very difficult to process wind turbine blades when they are removed from turbines at their end-of-life. The first generations of wind turbine blades are now being decommissioned. Over the next few decades there will be a huge increase in blade waste which is predicted to rise from 100,000 tonnes per year in 2025 to 200,000 tonnes per year in 2033 [2,3]. Figures from the International Energy Agency (IEA) support this, projecting that wind generation will rise from approx. 1,300 TWh in 2018 to 3,300 TWh by 2030 [4], hence blade waste will continue to rise because there is a more or less constant relationship between the power of a three blade horizontal axis turbine and the mass of the blade material (one GW of generation requires approximately 10,000 [5,6] - 14,000 [7,8] tonnes of blade material. Although the entire turbine assembly can potentially be recycled at present to a great extent (80%–90% by weight) [9,10], wind turbine blades are challenging to recycle. Turbine blades have a complicated geometry and structure, and are composed of several different materials. Most of the mass in turbine blades is glass fibre reinforced polymer (GFRP) and/or carbon fibre reinforced polymer (CFRP), both of which are difficult to process at the end-of-life of the blade [8,11].

Guidance for processing these blades is to be found in the waste management hierarchy (WMH). The European Commission, in the Directive on Waste Management [12], and the United States Environmental Protection Agency (EPA) [13] are in agreement on a priority sequence for processing waste, the WMH. Applying this to blades, the WMH gives first place to waste avoidance (long-lasting blades and a second-hand blade market), next to repurposing (using blades to make new products), recycling (breaking down the materials in the blades to make new products), energy recovery (incineration) and last, disposal by landfill, which is not a sustainable solution.

In this study a structured literature review compares the WMH and the recent literature concerning end-of-life wind turbine blade processing. This is done in a systematic and objective way using the first four methods of the WMH to select the literature to be reviewed.

There is little research into the two highest priority methods of the WMH namely, waste avoidance and repurposing, while there is a great deal of research into recycling (e.g. [14,15]), and little attention given to energy recovery. The literature frequently uses a circular economy approach to blade waste (e.g. [6,16]) but rarely uses circular economy business models. On a practical level the most common methods to deal with blade waste are incineration and landfill [8,17]. This suggests that there are barriers to the top two methods of avoidance of waste and repurposing. These barriers are identified and solutions proposed.

It is seen that there are frequent reviews of the progress of the technology used for blade processing. This has been necessary due to the speed of technological progress. Among these reviews are three recent structured literature reviews. Paulsen and Enevoldsen [18] focus on blade recycling and after thoroughly reviewing the methods which are technically available, find that only co-processing blades in cement production is commercially viable and scalable. Eligüzel and Özceylan [19] take a wider view of turbine recycling and identify that more work needs to be carried out into supply chain operations, location, regulatory and managerial issues. The review finds that there is a great deal of attention paid to offshore wind turbines. Lund et al. [20] focus on wind turbine blades. Their paper proposes a decision making procedure which takes into account economic, environmental and social criteria to distinguish between four different methods to cut wind turbine blades. The results are validated by industrial waste experts. These structured reviews consider the technology up to the first half of 2022. More information concerning the literature may be found in [21]. Other reviews, not following a formal structured methodology include, in order of increasing age, [8,9,14,22–34], and [35].

This study adds to the existing literature in four ways. It follows the systematic methodology of a structured literature review, it takes its

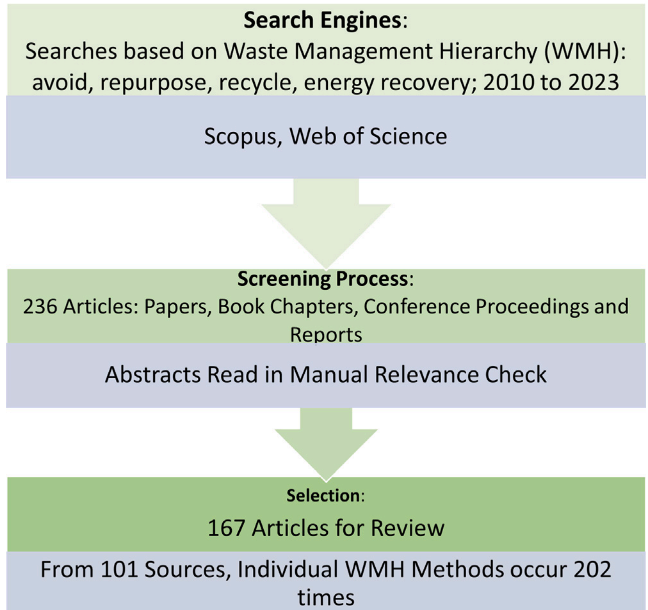

Fig. 1. Summary of literature selection method.

search criteria from the WMH which provides objectivity to the search results, it offers an update on the progress of the technology and, most importantly, it proposes solutions based in circular economy business models. In this work obstacles to sustainable end-of-life processing of wind turbine blades are identified from an objective search of the literature. Circular economy business models to overcome these obstacles are then proposed.

Section 2 describes the method used for the structured review of the current literature, and presents some high level findings. In Section 3 the current processes for end-of-life blades are described in some detail and barriers to sustainable processes are identified. Solutions are proposed in Section 4. Section 5 concludes.

2. Method

A structured review of the current literature regarding the processing technologies available for wind turbine blades at their end-of-life is conducted using four particular sources, [36–38] with particular emphasis on [39]. The ways to populate the list of articles to be considered for the review are defined, as well as the selection process after the initial results are returned from search engines, as described in Fig. 1. The selection criteria are discussed in Section 2.1 followed by a quantitative description of the relevant literature in Section 2.2, and high level findings in Section 2.3.

2.1. Selection criteria

The time span, search engines and search terms are now considered. Literature from 2010 onward was included in the search, this date was chosen for two reasons, firstly the technology in the field of composite recycling is changing quickly therefore a relatively recent starting date is needed and secondly, the literature up to 2010 suggested that incineration with or without heat recovery and landfill were the only ways to dispose of used blades for the foreseeable future [40]. Since 2010, some new methods such as co-processing, pyrolysis, solvolysis and mechanical recycling have become available. 2010 is therefore chosen as a starting year for this review.

Searches were conducted using Web of Science and Scopus so that only recognised and highly reliable sources would be considered. Searches were carried out at the end of June 2023. To ensure that the literature is selected in an objective manner and following the prioritised methods in the WMH of [12,13] (avoid, repurpose, recycle and recover energy), the following four search strings were used:

- wind AND turbine AND blade AND waste AND avoid
- wind AND turbine AND blade AND repurposing
- wind AND turbine AND blade AND recycling
- wind AND turbine AND blade AND (incinerate OR incineration).

It was decided that searching for the terms ”energy” and ”recovery” would produce too many false hits, while ”incineration OR incinerate” would be more useful. The search engines produced 236 articles. Each abstract was checked for relevance, this produced 167 relevant articles.

2.2. Quantitative description of the selected literature

The relevant articles were remarkably diverse coming from 101 sources including journals, book chapters, conference proceedings, and reports. This diversity reflects the width of the task of processing end-of-life blades spanning composite recycling, renewable energy, sustainability, chemistry and engineering. To see how the literature has expanded in the period 2010 to 2023, a list of which of the 167 articles refers to each method is provided in Table 1. This list served as the basis for Fig. 2 which shows the distribution of the 202 mentions of any of the top four WMH methods through time.

2.3. High level findings

The first finding is that there has been increasing interest in recycling of turbine blades in the last 14 years, and that this has been focused almost entirely on methods to extract the resin and fibres from GFRP and CFRP. The second finding is that there was very little attention paid to repurposing or waste avoidance, despite these being higher than recycling on the WMH. Thirdly, there is little research on circular economy business models despite a reasonable interest in the circular economy connected with blade recycling. There were 37 papers dealing with the theme of circular economy and only 17 looking at circular economy business models. An exploration of the literature on the current end-of-life processes follows in Section 3, with a SWOT analysis carried out in Section 3.4.

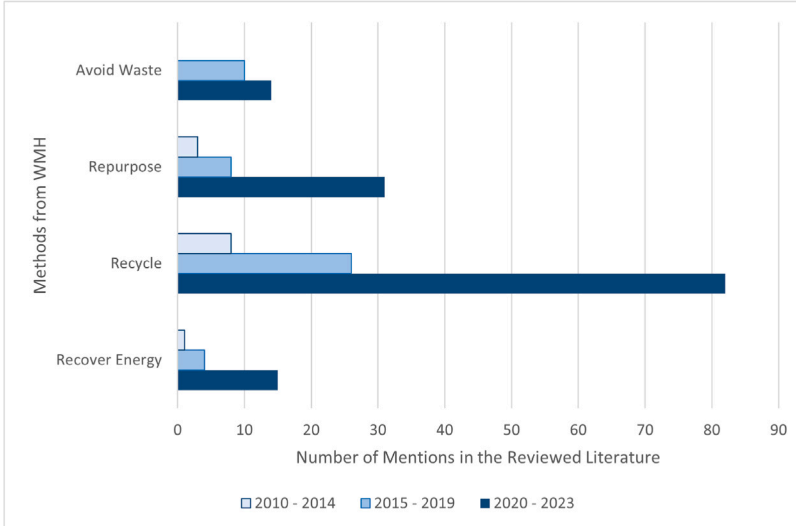

Fig. 2. Numbers of methods from the waste management hierarchy (WMH) appearing in papers over time.

Table 1
Sources arranged by time and method.

Method	Years	N	Sources
Avoid	2020–2023	14	[23], [41]; [27], [42], [43], [44], [15], [14], [45], [24], [46]; [47], [48], [49]
	2015–2019	10	[50], [51], [52], [53]; [11], [54], [9], [55]; [56]; [57]
	2010–2014	0	
Repurpose	2020–2023	31	[20], [58], [59], [60], [23], [61], [8], [62]; [63], [24], [15], [42], [14], [27], [64], [65], [66], [67], [68] [69]; [70], [71], [72], [73]; [3], [74], [75]; [17], [76], [77], [78],
	2015–2019	8	[79], [80], [81]; [9], [11], [82], [83], [84],
	2010–2014	3	[85]; [86]; [87],
Recycle	2020–2023	82	[20], [88], [58], [89], [90], [41], [91], [92], [93], [59], [94], [95], [96], [97], [60], [22], [98], [99], [100], [101], [23], [102]; [24], [103], [104], [105], [15], [42], [65], [106], [107], [19], [45], [108], [109], [25], [110], [14], [111], [44], [26], [112], [28], [113], [114], [115], [116], [27], [117], [118], [28], [65], [119]; [120], [70], [121], [122], [71], [123]; [124], [125], [126], [127], [48], [18], [128], [129], [120], [130], [131]; [17], [132], [133], [134], [135], [136], [137], [138], [139], [140], [141], [142],
	2015–2019	26	[52], [33], [143], [144], [30], [145], [146], [147], [148], [32], [149], [150], [151], [152], [153], [154], [155]; [9], [11], [156], [157]; [158], [159], [160], [161]; [162],
	2010–2014	8	[34], [163]; [164], [85], [165]; [35], [166]; [167],
Recover Energy	2020–2023	15	[20], [88], [58]; [24], [103], [104], [105], [15], [42]; [70], [121], [122], [71], [123]; [17],
	2015–2019	4	[52], [33], [143]; [9]
	2010–2014	1	[35]

3. Current end-of-life processes

The end-of-life processes are examined under the three WMH methods of repurposing, recycling and recovery of energy. Avoidance of waste, the first method of the WMH, is discussed at the end of this section. Repurposing involves blades being cut and refashioned to make new products including houses, roofing, construction materials and furniture. This is done without substantial chemical change to the blade material but may involve considerable cutting of the blades, see Section 3.1. Recycling in Section 3.2 includes the extraction and separation of the fibres and resins from the blade material using mechanical methods, see Section 3.2.1, heat (pyrolysis), see Section 3.2.2, or chemical solvents (solvolysis), see Section 3.2.3. Another example of recycling is the use of crushed blade material in manufacturing cement by co-processing see Section 3.2.4, in these examples of recycling there is considerable chemical change to the blade material. There is also research into making blades more easily recyclable, see Section 3.2.5. While energy recovery is not as circular as the other alternatives, it is considered here in Section 3.3, because it is currently a popular way to deal with blade waste [84,168]. A comparison of the current repurposing, recycling and recovery technologies and their commercial potentials are presented in a SWOT analysis in Section 3.4 and Table 2.

3.1. Repurposing blades to make new products

There is a range of opinions in the literature regarding repurposing of blades. Several studies [17,123] and [134] do not consider repurposing to be a useful solution believing that it is not capable of handling the volume of material from decommissioned wind farms, but [71,138] and [178] support the idea of repurposing. Additional support is found from the work of the Re-Wind Network [179] of which the authors are members, and the Superuse-Studio [180], both groups have found many uses for blades by repurposing them.

Repurposing makes use of the rigidity, low density and resistance to environmental degradation of wind turbine blades. There are a number of uses considered in the literature: roofing [72,77]; furniture and skateboards [11,70]; housing and other architectural components [82,181]; pedestrian and cycle bridges [169,171]; bleachers (stands) for spectators at outdoor events, noise barriers, wave attenuators, piles, cylindrical tanks, mobile phone masts, building facades, roof trusses, chimney liners, geo-retention barriers, louvres, pods, barriers and outdoor park equipment [5,82]; bus shelters, public seating, playground items, marine structures and art installations [172,182]; bicycle

Table 2
SWOT analysis for blade end-of-life processing technologies.

	Strengths	Weaknesses	Opportunities	Threats
		Repurposing		
Electric Poles [72,73]	High value product, can be used in place of wooden or concrete poles.	Logistics difficult as it requires transport of longer blade lengths and needs many of the same type of blades.	Can hold telephone, lighting, or power cables, or telecomms dishes.	Technically difficult to design; Public perception of the aesthetics has not been tested yet.
Furniture [70]	Medium value product; Proving to be in high demand. Easy to transport. Uses shorter pieces of blade material	Mass production is difficult as blades differ. Provenance difficult.	The supply of used blades is about to increase. Fits green procurement market.	There may be problems with cutting technologies and dust. More expensive than conventional products.
Pedestrian and Bicycle Bridges [62,68,70,169–171]	High value product	Currently a bespoke product rather than mass market. Long procurement time.	Could be adapted for mass market. Fits green procurement market.	Difficulty having to test each type of blade. Public perception of the aesthetics has not been tested yet.
Roof Beams [5,72,73,77,82,83]	Relatively light roof beams, cheap to obtain.	Curved shape means the joints needs specific attention.	There are many blades about to be available.	Difficulty due to matching the available blades to buildings.
Panels [84,166,172]	The product is widely used in DIY and construction.	At an early developmental stage without commercial testing yet	Can cope with large quantities, many uses of the panels are possible	Could face problems with dust and subsequent disposal
Needles for Concrete [173]	Improves the concrete in some respects.	May not be commercially viable.	Together with co-processing this offers a greener version of concrete.	Long term properties are not known yet.
Aggregate or Filler [10,124]	Chopping and grinding produces a standardised product.	The product is cheap; provenance may be difficult to verify.	Can cope with large quantities.	May be environmental problems with dust.
Glass Fibre Waste from Production Added to Geopolymer [160]	Improves the geopolymer strength and durability.	Small market for geopolymer.	Green alternative to Portland cement.	Long term properties not well known.
		Recycling		
Mechanical [22,30,31,70,84,172,174–176]	Established technology and a pre-processing method for pyrolysis, solvolysis and co-processing.	Creates relatively low value products.	Easily scalable as it uses existing technology.	Creates dust and may be subject to increased environmental regulation.
Pyrolysis [40,120,121,124,136,145–147,172]	Promising technology, CFRP likely to be commercial ahead of GFRP.	Both the GFRP and CFRP fibres produced by this method are more expensive and weaker than new fibres.	Possible breakthroughs in the future.	GFRP may never manage to be commercially viable.
Solvolysis [120,124,174,177]	Causes less damage to the fibres than pyrolysis.	Only happening in the lab at present, there are potential environmental impacts from using solvents.	Future possible improvements may radically change the commercial problems.	Future possible improvements may not radically change the commercial problems.
Co-processing into Concrete [10,11,124,139]	Currently available process which does not produce ash	GFRP replaces silica in cement manufacture, but this is a low value use of blade material.	Solid market demand, sell it as a recycled product	Cement making is a major source of GHG
		Recovery of Energy		
Energy Recovery [10]	Quick and can be scaled up.	After incineration there is still a large amount (60%) of ash for landfill.	Large supply of blades into the future.	Emission allowance prices for CO_2 output, regulatory risk for possible pollution from fumes.

shelters [183]; artificial reefs [184]; strengthening concrete [173]; and, thermal insulation and noise cancelling screens [6].

While repurposing faces challenges due to the size of the blades [35] and problems inherent in cutting through composite materials [185,186] some useful analysis of various methods can be found in [70] showing that there are promising results for some products from economic, social and environmental points of view. Particular parts of blades lend themselves to particular purposes. The circular root section nearest to the hub is ideal for large diameter pipes, or circular bases for cattle feeders. The gentle curve along a blade is ideal for artistic and playground uses. There is very little of the blade material which is flat, the exception being the spar caps which are inside the blade and are not easily removed. These applications are competing with existing products such as plywood, medium density fibreboard, PVC sheeting etc. Some of these are indeed novel suggestions, but they have not yet achieved a large enough scale to deal with the amount of blade waste which will be generated in the next ten years [3,162].

3.2. Recycling of blade material

Recycling of turbine blades is made difficult because of their complex composition, the use of thermoset resins and, the physical size and location of the blades [20,35]. There are several methods to recycle blade material by separating the glass or carbon fibres and resins by mechanical means, pyrolysis or solvolysis. Recycling can also be achieved for GFRP by co-processing. It is also possible to re-designing the blade manufacturing process to make more easily recyclable blades. These methods are now discussed.

3.2.1. Mechanical

Mechanical recycling begins by cutting and crushing the blade material to such an extent that the particles mainly composed of resin and the particles mainly composed of fibre, are different sizes, and can be separated by using sieves and cyclones [31,175]. The main advantage of mechanical separation of fibres and resin compared to pyrolysis and solvolysis, is its simplicity and generally lower energy requirement. As the degree of physical intervention increases there is less resin residue on the fibres, but there is also more damage to the fibres which are therefore less valuable [22]. Mishnaevsky [22] compares [31] and [70], the former finding that mechanical recycling is preferable to repurposing, the latter finding the reverse. Mechanical recycling is currently being carried out by many recycling firms, for example, in USA by Fibecycle [176] and in Ireland by Plaswire [187].

Shredding blades and adding new thermoset resin to make panels was discussed in [84], the resulting panels could be used as floor tiles or plastic road barriers. Cutting and grinding wind blades may be used as way to produce aggregate. [172] found that this aggregate can be used to make board and railroad ties (sleepers). This product is of low value, but cutting and grinding has been found to be a practical (though energy intensive) way to dispose of the blade material by [174] and [30]. These authors go on to state that the short fibres of GFRP can strengthen gypsum blocks which are used for partition walls, these blocks can be made fire-proof, but are not for load bearing walls. Powdered GFRP can also be used to strengthen plastic fibre drain covers.

There has been recent research looking at the use of GFRP fibres to make stronger geopolymers [160]. These can substitute for cement and are more resistant to freeze thaw and acid than regular Portland cement but are brittle. The GFRP fibres improve the geopolymer strength. Blades have been ground and added to concrete by LM Wind Power [11]. Adding ground GFRP to concrete has been found to reduce its strength [188], but cutting the GFRP into small cylindrical pieces (diameter 6 mm and length 100 mm), known as needles, and adding these pieces to concrete has shown itself to be useful in improving the ability of concrete to absorb energy [156,173].

3.2.2. Pyrolysis

Glass fibres and carbon fibres can be extracted from the composite blade material (GFRP and CFRP) by the use of heat in a process known as pyrolysis. Pyrolysis is carried out in the absence of oxygen at temperatures near to 500 °C; the heat evaporates the resin which can then be converted to syngas and sold [172]. Compared with new fibres, recovered fibres are significantly degraded, but are still useable [121]. Pyrolysis is a promising technology [136] and fibre extraction may become a commercial possibility for CFRP as carbon fibres are quite valuable [146,147], but this is not the case yet for glass fibres for which pyrolysis is not commercially viable [120,145]. The heat for pyrolysis may also be provided using microwaves, this also produces syngas and fibres which are weaker than new fibres. In research by [166] a mixture of 25% recycled glass fibres were processed using microwave pyrolysis to make a reasonably good laminate. A drawback of microwaves is the need to remove any metal components in the blade material [172].

3.2.3. Solvolysis

Recycling fibres chemically by solvolysis is expensive [174] and, as is the case for pyrolysis, recycled fibres are not strong enough to make new blades [120]. Most of the methods, such as fluidised bed, solvolysis and microwave heating are either still lab techniques or only at the pilot stage [177]. A proven technology, co-processing, is now considered.

3.2.4. Co-processing

In co-processing, GFRP is incinerated in a kiln with other feedstock to make cement. The glass fibre is used directly in the cement and the resin replaces some of the fuel needed to provide heat. Co-processing is more environmentally beneficial than landfill or energy recovery [70,139]. As well as making cement, the process does not create ash and so avoids any need for landfill. Academic studies have shown that it may be commercially viable [52,120], but places a low value on the GFRP in the blades. Co-processing may therefore be a very useful way to deal with blade waste in Europe [11,189] but at present with only one facility in northern Germany, there are limits to the amount of blade waste which can be currently co-processed [190] as well the waste being in limited and irregular supply [191]. Co-processing is also being undertaken by Veolia in USA [192,193].

3.2.5. Recyclable blades

There is currently a considerable volume of research into two new construction methods for blades, one is to use a resin which dissolves in mild warm acid another is to make the blades from thermoplastic materials [50,51,194]. There have been recent media announcements from Siemens Gamesa [195], GE [196] and most recently, Vestas [197] promising recyclable blades [145] and from National Renewable Energy Laboratories (NREL) [198] where a 13-metre thermoplastic resin blade has been tested. These new technologies would ensure that GFRP and CFRP would be easier to recycle in the future.

3.3. Recovery of energy by incineration

There is useful energy to be recovered from GFRP, and if the higher value recycling and repurposing methods are not commercially viable or not capable of handling the volumes involved, then incineration with heat recovery is a practical alternative as has been demonstrated by Vestas [40]. Incineration does have its problems with toxic gases escaping depending on the temperature [174]. In addition, there are many social and political problems associated with incineration [199], but it is viable. [172] and there is a market for the ash as high-grade clinker. This is not straightforward as the blades need to be cut into relatively small pieces before incineration and incineration of GFRP causes some damage to flue systems [120]. CFRP should not be incinerated because of the small carbon fibres in the flue gas which are a pollutant [200]. The leading methods of dealing with blade waste are currently incineration and landfill because of the high cost of recycling blade material to extract the fibres [17,52].

3.4. SWOT analysis for repurposing, recycling and energy recovery

The strengths, weaknesses, opportunities and threats for different end-of-life processes are presented in Table 2. This is based on the literature as indicated, and on the opinions of the authors. The SWOT analysis assists the identification of barriers to sustainable end-of-life processes discussed in Section 3.5.

3.5. Barriers to avoidance, repurposing and recycling

The problems for avoidance, repurposing and recycling are considered here with a view to possible solutions which will be proposed in Section 4.

Avoidance of waste is discouraged by the payment structure for blades, namely that the original equipment manufacturer (OEM) is paid for selling blades, and therefore profits when new blades replace those which have been removed from use. If blades were to stay in use for longer, then waste could be avoided.

A lack of information about the use and repair history of blades is a barrier to the second hand market, which would provide a means to avoid blades becoming waste before their useful life is over. Repurposing is made quite difficult due to lack of information on the design, shape and content of used blades, for example, it can be difficult to know where to cut blades [9,11]. This lack of information is due to some OEMs being slow to release detailed plans due to commercial considerations, and from the practice of wind farms going through several owners and information being lost in the process. Repurposing is also restricted due to the lack of investment required to set up repurposing on an industrial scale.

A problem inhibiting widespread adoption of recycling is lack of financial motivation. At present, the only recycling process which is near to commercial success is co-processing which has limitations. In addition, the lack of information about the content of blades is a barrier, making it difficult for example to know where to cut through the blades.

The identification of the problems for blade recycling/repurposing based on the SWOT analysis in Section 3.4 leads to some proposed solutions which follow in Sections 4.2–4.4 following a discussion of circular economy business models (CEBMs).

4. Circular economy business models

4.1. What is a circular economy?

A circular economy re-uses its materials so that goods are in a constant cycle of use, repair, repurposing, recycling etc. leading to re-use. Circular economy business models (CEBMs) enable this by arranging financial rewards to support a circular economy. The main problem for a circular economy is that the incentives for the linear economy are already in place. Circular economy ideas such as re-manufacturing, sufficiency and slowing consumption, are not profitable for current manufacturing businesses [201]. This is because manufacturing businesses focus on sales of products rather than provision of the services for which the products are made. Service businesses are somewhat different, they may make a transition to circularity more easily since they may directly benefit from savings brought about by product longevity and better equipment quality. However at present, blade recycling is not profitable [74] thus, a blade manufacturer has little incentive to invest in designing products for easier recycling or repurposing. A new payment structure for OEMs should be developed to encourage circularity, information about blades should be made available and a financial incentive for sustainability should be provided.

Inspired by these problems, three CEBMs are proposed:

- A payment structure for provision of turbines by original equipment manufacturers (OEMs) which rewards OEMs for long blade life, (Section 4.2);
- Providing blade information to facilitate a market in used blades, recycling and repurposing (Section 4.3).
- A more flexible and widespread use of compliance bonds which pay out when successful sustainable processing has occurred (Section 4.4).

4.2. Payment structures

A starting point for a circular economy business model is to look at the provision of the blades themselves. Three different payment structures are put forward for the provision of wind turbine blades, these are compared following [202], they are: take-back management, product leasing, and pay-per-use.

The first, and least radical change to the usual payment structure, is take-back management, which is one aspect of extended producer responsibility [105,203]. This means that the OEMs are obliged to take back the blades when they are at their end-of-life. This encourages OEMs to design the blades for recycling and avoids wind farms being responsible for disposal of the blades. A more radical suggestion is to move away from the standard user owner model. A weakness of the standard model is that the owner retains responsibility for decommissioning the wind farm which will happen at the least productive time for the wind farm, tempting unscrupulous wind farm owners to avoid their responsibilities. Take back management would reduce some of the costs of decommissioning, but the following two models, leasing and pay-per-use, would remove this difficulty as ownership would stay with the OEM.

The second payment structure, leasing, involves the owner of the wind farm paying for the turbines on a per-time basis, while the ownership of the equipment remains with the OEM as does responsibility for maintenance. This would have the advantage that the OEM is rewarded for making a product which lasts a long time [204]. In the case where an OEM raises finance for turbines from the bond market, this model can be arranged to match the timing of coupon payments and income from users, thus stabilising the OEM's cash flows. From the point of view of the wind farm owner, this model leaves the wind farm exposed to the risks of balancing the variable income from selling power and the constant payments for the lease. This risk may be alleviated by a power purchase agreement which is a swap of the variable market price of electricity for a fixed price, given by an intermediary power company.

The third payment structure is for the OEM to charge the wind farm per rotation of the turbine, or per MWh of energy produced. This pay-per-use model would encourage the OEM to make long lasting blades and would provide the wind farm with a payment structure which is more directly connected to its own interests [205]. The pay-per-turn model may be preferable to the OEM as it does not expose the OEM to the operational risks from the rest of the turbine, that is, the OEM's liability is restricted to the blades for which it is directly responsible. A pay-per-MWh model may be attractive to the wind farm owner as it reduces operational risk considerably and matches outgoings and income.

Of these three payment structures, pay-per-turn most closely matches the responsibilities of the two parties to their incomes. The OEM is rewarded for making efficient blades which last a long time and do not need excessive maintenance. The wind farm is rewarded for selecting a suitable site, negotiating permissions and building the infrastructure including the grid connection. While both sides carry risks, they are able to control these risks by their own efforts. The only common risk is wind speed which is highly variable on a day-to-day basis, but which, in the longer term, depends on the location of the wind farm which is, of course, known to a great extent in advance. For a wider discussion of the main limits and challenges of a transition to a circular economy see [206].

The switch from selling blades as products, to selling the provision of a blade, has a desirable by-product, namely, that it reduces some of the considerable capital hurdle and some of the risk for new entrants to the wind farm business, for example community ownership is made easier. One of the principal difficulties for developers wishing to build a wind farm is the huge initial cost, approximately 75% of the entire cost of running a wind farm over its lifetime is taken up by design, equipment purchase and installation, all of which happen at the start which is a considerable barrier for smaller developers and community led wind farm development [207,208].

4.3. Information exchange

It is difficult to know the exact size and shape of a wind blade even for the owner, and so a service which provides this information can be of great assistance. The root of the lack of information about blades is that this information is commercially valuable to the OEM, particularly at the time of manufacture and so, even the purchaser of a blade may not be told the exact design of the inside or the outside of the blade [190]. These problems are exacerbated if a wind farm has had a series of owners in its lifetime, as often records are lost.

There are commercial problems for those wishing to sell goods which are made from blades, since they will need to be able to authenticate the provenance of their goods. This is because customers wish to be sure of the authenticity of the claim of sustainability for goods which command a premium in the market [209]. In addition, investors in companies working in sustainable industries wish to be able to authenticate claims of sustainability. This is important because there is a huge amount of interest in sustainable investment. The size of the bond market is approximately US$100 trillion of which US$1.4 trillion has been issued as "Green Bonds", and this part of the bond market is increasing rapidly [210]. Such Green Bonds must be certified and authenticated as being sustainable. In this regard, the European Commission has proposed a taxonomy for sustainable investment so that investors may be able to understand what it is that they are buying [211].

A business which sells blade information can be part of a solution to these problems. A platform can allow buyers and sellers of blades to meet and to match their requirements, it can also offer a facility where the provenance of blades and turbines can be verified. There are already successful platform buy and sell sites such as Ebay, Craigslist and DoneDeal, and there are some specialised sites for the wind energy industry [212,213], and even a specialised site for wind turbine blades [214]. Ideally an OEM will provide information for its blades but if this is not done there is an opportunity for businesses to use Lidar or other technologies to provide replacement information. An example of this technology is the Blade Machine being developed by Re-Wind in Georgia Tech which aims to provide detailed plans of blades for repurposing [81]. Certification for structural integrity for repurposing blades to become part of bridges or buildings is also vital [136,184], and therefore valuable. The needs of the market for repurposing, recycling and re-use would therefore provide a basis for an information exchange which could provide plans and provenance information for used wind blades.

While it is understandable that an OEM will not compromise the first life of a blade in order to make the second life easier, there are some things which will assist the second life such as keeping easy access to the detailed plans of the blades and embedding markers so that these plans may be easily used [74]. The cost of these markers and data storage is trivial compared with the cost of producing a blade. Successful design for recycling will enable product-as-service models since the manufacturer can benefit from the recycling opportunity not afforded to competitors [29] since the OEM will be able to optimise their product for their own recycling processes. This of course depends greatly on the OEM's cooperation in providing information about the blade's design, but such cooperation may not always be available.

4.4. Compliance bonds

Financial incentives can be used to promote progression from linear to circular business models and address market failures in the renewable energy sector. Applying traditional strategies such as command and control regulation or Pigovian taxation to energy related environmental problems may stifle market expansion and fail to provide sufficient motivation for businesses to invest in circular innovation [215]. Alternative approaches should be considered to overcome undesirable behavioural and systemic patterns embedded in energy generating industrial processes and supply chains.

Assurance or compliance bonds offer a flexible and transparent regulatory option, providing financial investment in desirable end-of-life processing and the potential for circular innovation. Compliance bonds pay out when an action agreed at the outset of the bond, in this case repurposing or recycling of a wind turbine blade, has been carried out, see Table 3. Due to the scale of global renewable and non-renewable energy generation and their importance to supporting human welfare, it is important to develop methods to reduce undesirable environmental and social externalities. Psychological and behavioural conflicts exist within these industries which limit prosocial actions. Temporal factors exacerbate these failings causing imbalances between short-term profit motives and long-term sustainability and circular innovation. Mandatory investment in compliance bonds can close the gap between individual business motives and broader social and environmental priorities. Bonding can also link assets with their potential future value as recycled or repurposed material inputs.

4.4.1. Market failure

Platt [216] frames the problem to be addressed as a "social trap" and more specifically a "countertrap" where the pursuit of an advantage by an individual entity prevents it from acting in ways which may have a significant benefit to the wider society. Similarly, the "tragedy of the commons" [217] describes how individual exploitation of finite resources can provide individual benefits, but societal failures.

Evidence from the U.S. shows that within mineral extraction sectors, operators often act with negligible moral compulsion and tend towards amoral profit maximisation, particularly once the decommissioning phase approaches [218]. Statistics from the U.S. estimate the existence of 190,000 abandoned underground petroleum tanks, 57,000 orphaned unplugged oil or gas wells, and 557,000 abandoned mine sites [218]. Data for wind blades is less complete given that wind blade decommissioning has only become an area of interest in the past five years based on the number of published papers on the topic. However, the low intrinsic value of wind blade waste (particularly glass fibre composites) coupled with the complexity of recycling and repurposing, suggests a potential market failure may exist.

This potential failure is related to the limited economic attraction of complex circular end-of-life solutions compared with less complex linear options such as landfilling or incineration. The considerable time gap between manufacturing and end-of-life processing also creates a disconnection between the initial capital investment and the allocation of resources for future circular solutions and innovation. In the absence of market incentives, it is not logical to assume decommissioning will take place to a high environmental standard.

4.4.2. Pigovian limitations

Pigovian taxation is widely deployed as a strategy to manipulate and control consumption and waste behaviours. It is particularly effective at addressing undesirable externalities such as health impacts and environmental damage [219]. This form of financial intervention can have the effect of limiting consumption while also providing an option to pay/charge the tax rather than changing behaviour. There are typically few direct links between the revenue generated and the allocation of funds for redressing the environmental impact of individual products and services. Rather, funds collected may be allocated to sectoral initiatives at the discretion of the receiving institution (for example taxes raised from a plastic bag levy may be allocated to support voluntary environmental groups).

The extent of available investment capital in renewable energy sectors could reduce the effectiveness of a Pigovian tax to drive pro-social behaviour. A regulated business or sector is likely to choose paying a relatively inconsequential tax rather than investing time and resources innovating for circular processing solutions. The Pigovian system therefore risks becoming a fund-raising exercise for state/regulatory bodies rather than its intended purpose, to drive behavioural change.

Limiting blade manufacturing and consumption is not a priority underlying financial incentivisation for circularity given the need for the global expansion of renewable energy. Mandating producer/user responsibility is also preferable to the Pigovian option to pay a premium as a substitute for changing behaviour. Therefore, an alternative form of financial incentive is required to ensure responsible industry practices and circular innovation in the context of necessary sectoral growth. Rather than placing a tax on wind blades to drive circular processing, it is worth considering the effectiveness of creating circular value which is directly linked to an asset over its lifetime. By increasing the end-of-life value of an asset, repurposing and recycling can become more attractive economic propositions.

4.4.3. Refundable assurance bonds

Assurance bonding (also called a compliance or performance bonds) is proposed as a flexible and effective financial system to address these issues [215,220]. Refundable Assurance Bonds have been used to increase adherence to environmental regulations in highly polluting industries such as coal and oil extraction [221]. Bonds have been used in environmentally sensitive areas to ensure that changes to the environment from business activities such as structural developments, are fully decommissioned and the environment restored to an acceptable standard [222]. Research has also been conducted into compliance bonding in systems with exceptionally large time scales such as carbon capture and sequestration [223]. Previous work has also showed that even when bonds are used to cover unlikely events such as emergency clean-up of environmental accidents, the existence of a clearly defined contract between regulator and operator in the form of a performance related bond, encourages the financial and operational aspects of long term regulatory requirements to be incorporated into planning decisions in the early stages of a project [224].

A comprehensive bonding system has been in operation in the U.S. on a state level since the enactment of the Surface Mining Control and Reclamation Act (SMCRA) in 1977. The value of outstanding coal mine surety bonds was estimated at $7.8bn in 2018 [225]. A further federal system was proposed in the U.S. in response to the failures evident in the system of self-bonding. Self-bonding relies on collateral rather than bonds to ensure a firm's decommissioning responsibilities are fully financed. These commitments are frequently circumvented by business operators declaring bankruptcy before their stated financial obligations can be enforced or environmental damages addressed [221].

Mandatory assurance bonding by comparison, creates a contract that requires sufficient funds are legally set aside in the initial licensing/manufacturing stage to fund future processes required to meet regulatory pollution controls and decommissioning requirements [221]. These funds are non-recoverable by a going concern or creditors of an insolvent firm without first meeting the contractual regulatory standards. Given the expected life span of wind blades, assurance contracts linked to assets may be preferable to those linked to operators/manufactures. This would allow blades to change ownership over their lifetime while the funds invested for end-of-life processing would transfer with the asset.

The proposed U.S. EPA/CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act 108(b)) [225] federal bonding system for coal extraction licenses in the U.S., envisaged the pricing of bonds incorporating indirect costs incurred in the event of the regulator being burdened with remedial works due to industry non-compliance [226]. In the context of wind blade assurance bonding, this premium could provide added incentive to operator firms to avoid indirect regulatory costs of non-compliance. By efficiently meeting regulatory standards, the processor could potentially receive a bond refund in excess of the costs incurred by them in the decommissioning process.

By linking bond contracts to individual assets, it would be possible to ensure their optimal processing at end-of-life while also providing transparency and traceability of the regulated asset throughout its life-cycle. Maintaining a central database of outstanding assets could assist a regulator to track the legal ownership, volume, life-cycle stage and location of assets in operation. There is potential to cross reference this data with the value and contractual terms of linked assurance bonds to ensure there is sufficient investment to meet future circular decommissioning requirements, and of course to fulfil the aims of the information exchange of Section 4.3.

Table 3
Compliance bond states.

Asset stage	Bond state	Circular benefits
Manufacture	Issued to manufacturer at a price that covers circular decommissioning at end-of-life	Assurance of eventual asset circular decommissioning from point of manufacture
Sale to User	Transfer to owner, owner pays manufacturer full consideration (blade price + bond price)	Circular processing responsibilities transfer with the asset. Traceability throughout its life.
Lease to End User	Remains with the lessor to finance end-of-life processing	Reducing risk of lessor being unable or unwilling to cover processing costs
Premature Failure	Early redemption on processing completion	Advantage over fixed dated bonds, incentive to process in a timely manner. Overcomes unexpected cost/cashflow issues
Life Extended	Apply for extension on redemption date limit	Data available on life extension, funds remain available for eventual decommissioning
Owner Insolvency	Linked to asset, ringfenced funds	Funds redeemable on completion of asset processing or bond remains with asset.

Recent research in the field of blade circularity is heavily skewed towards recycling of blade materials through processes such as mechanical recycling, solvolysis and pyrolysis (see Section 3.2). Although these are important developments in terms of an overall circular economic model for wind blades, shorter loop options in the 9R framework between the collection of waste and recycling receive less attention. The 9R framework is a more detailed version of the WMH covering the same methods. (The nine R's are: refuse, rethink, reduce, re-use, repair, refurbish, remanufacture, repurpose and recycle. The interested reader is directed to [227].) Shorter loop solutions may be less scalable and therefore may be less attractive in terms of investment of financial and non-financial resources. Bonding can help to close that gap by financially incentivising shorter loop circular solutions by, for example, refunding 100% of the bond value for short loop refurbishing or reuse, with a reducing scale moving out towards longer loop processes such as the use of blade material in kilns for cement co-processing. The lowest percentage refund would then be available for the longest loop solutions such as incineration of blades.

4.4.4. Market size

Due to the scale of global wind generation a relatively small percentage of initial capital investment applied to mandatory bond investment per blade can create significant circular value. The Global Wind Energy Council estimates there are 341,000 operational wind turbines globally [228]. Taking an approximate cost per blade of €75,000, a 5% bond on three blades per turbine would value the potential global bond market at €3.8bn over the next life-cycle period if the number of turbines remained constant. Calculating the optimal bond price should consider current circular solution costs, innovation investment requirements, market conditions for wind energy investment and the social and environmental costs related to linear end-of-life processes. Innovations which reduce the cost of circular processing may be rewarded by reducing the mandatory bond rate.

4.4.5. Life-cycle discounting

For the purposes of effective bond pricing, carefully considering discounting factors over the large temporal life cycle of wind blades will assist in ensuring the net present value of bonds reflects the anticipated future financial outlays related to circular processing. Various discounting models exist and choosing an effective model can have a material effect on pricing. One straightforward method is to base long-term discount rates on equivalent long-term government bond yields [229]. By using this method, the discount rate can be accounted for by directly investing assurance bond funds in the government bonds on which the discount rate is determined. By reinvesting the resulting bond coupons, the assurance bond should reach a cumulative value at redemption in line with the relevant net present value calculation at the time of issuance. In an economic environment where prevailing interest rates are high, there may be an incentive for operators to postpone processing for as long as possible to take advantage of discount rates [226]. Firms may prioritise short-term cost reduction over initiating decommissioning and a longer-term bond refund. Processing costs must be incurred, and regulatory standards met before a refund is received. This may cause cashflow related conflicts exacerbated in the case of high discount rates. This issue may be more relevant however where there is no defined life-cycle expectation in industries such as coal extraction and where overall costs are extremely onerous. Wind blades by comparison have a finite life expectancy and therefore it is possible to impose a maximum term on bonds to provide reasonable time for processing but also a term limit to encourage timely action. Also, in the case of wind blades, processing technologies in development such as pyrolysis and solvolysis can offer time efficient circular processing, minimising the discounting effect in the time between the firm incurring processing costs and receiving a bond refund. Asset linked bonds also create the possibility of passing the blade to a processing firm with the attached bond intact. In this case the processing firm takes full ownership of the blade, processing responsibilities and eventual bond refund as income, removing any incentive for the operator to delay fulfilling their regulatory obligations.

Although technical solutions for embedding bond data in the linked asset are outside the scope of this study, by embedding data chips in the fibre of a wind blade for example, once re-manufactured to produce a new post-decommissioning blade based product, this data may be scanned by the processor to apply for the bond refund.

4.4.6. Political and industrial acceptance

The implementation of mandatory regulatory bonding is likely to be met with some opposition from interests which support free market, anti-interventionist economic models. However, several advantages exist which make asset linked bonds more attractive than other forms of regulatory controls. In contrast with taxation for example, bonded firms retain ownership of the financial instrument. Bonds that are reinvested in secure low yield government bonds should increase in value over their lifetime with the potential to offset provisions for future decommissioning costs on an owner firm's balance sheet. In this form, compliance bonds can be viewed as mandatory financial prudence rather than an onerous regulatory expense, particularly if there is support from the industry for the concept of circular end-of-life processing.

4.5. Policy experience from other types of equipment

The effort to introduce circularity to turbine blades can learn from other types of equipment. Policy interventions have worked well in Europe for electronic goods and vehicles, [35] since the European Commission brought in legislation enforcing extended producer liability and facilitating recycling by consumers for electronic goods [230] and cars [231]. Several car makers have voluntarily taken on an internal dismantling information system (IDIS) which, though bureaucratic, is useful for recyclers [231]. The IDIS database allows recyclers to know how to recycle each part of the cars from the manufacturers using the system, it also makes it easier for the manufacturers themselves to use their own used cars as a feedstock for new cars. On a world-wide scale there have been policy efforts by both the shipping and aircraft industries to facilitate recycling of materials. The Hong Kong declaration of 2009 [232,233] and the European Ship Recycling Regulations of 2013 [234], arranged for ships to maintain a list of the hazardous materials on-board so that at the time of recycling it is easier and safer to treat these materials properly. Maersk implemented a plan to make decommissioning easier and has improved the salvage value of their vessels by up to 10% [231], Airbus and Boeing have taken a lead by establishing their own end-of-life plans for aircraft [235].

In the car and electronics industries change towards a more circular economy has happened because of regulation mandating recycling; this might be expected to work with blades [74]. Any change towards compulsory recycling by manufacturers needs to have appropriate incentives [35]. In fact, care is needed to balance the difficulty of insisting on using a recycling system, while there is still not a consistent supply of blades to be recycled. At present the supply of blades for recycling is sporadic and lacks the volume to warrant a recycling industry, but the supply of blades will increase [134]. There needs to be a network to collect and process wind turbine blades, as well as a market for the recycled and repurposed products [124,236]. [120], addressing European needs, suggests that three or four processing facilities spaced around Europe would be optimal for blade recycling and that policy supports would be needed until 2050, by which time it should be economically viable. This will be an increasing issue as blades get longer particularly for offshore use [207]. It is now perhaps a good time for the wind industry to suggest policies, before policies are imposed.

5. Conclusion

The Waste Management Hierarchy is an agreed priority list of methods to deal with end-of-life products. The list is based on work by the USA EPA and the European Commission [12,13]. Applied to end-of-life wind turbine blades, it gives first priority to avoidance of waste, then repurposing, recycling, recovery of energy and lastly, disposal. At present most wind turbine blades are either incinerated (with or without energy recovery) or landfilled [3,162], these being the last two methods in the list. In this review the barriers to the first three methods have been examined using a structured literature review of 167 published articles. While the words used to search the literature were taken from the WMH, with the aim of providing an objective search process, it is always the case that some relevant literature may have been missed. This is a limitation of the work. Acknowledging this limitation, the review finds that financial barriers and information barriers exist. The following circular economy business models are proposed to overcome these barriers: an alternative payment structure (Section 4.2), an information exchange (Section 4.3) and the widespread use of compliance bonds (Section 4.4). CEBMs encourage sustainable consumption and production patterns, by enabling companies to adopt sustainable practices regarding the efficient use of natural resources.

A pay-per-use payment structure rewards original equipment manufacturers for making high quality durable blades and offers a closer link between the income and expenditure of wind farm owners. In addition, the initial capital barrier for wind farm developers would be reduced, this is particularly important for community-led wind energy developments. An information exchange matches blade owners and buyers, and can give access to the design details required for recycling, repurposing or a second hand market. Furthermore it could supply guarantees about the structural properties of blades, and the provenance of recycled or repurposed goods made from the blades. Compliance bonds, which pay the owner of the blade when the blade is sustainably processed at its end-of-life, would offer a direct financial support for recycling and repurposing of blades. In doing so the blade would move from being a liability to being an asset at its end-of-life.

Wind energy, with a properly planned waste management system, possibly including the solutions in this study, can certainly make progress towards the UN's Framework Convention on Climate Change

[237] and do so with regard to the UN Sustainable Development Goals (SDGs). In particular wind energy can make progress on affordable and clean energy (SDG-7), decent work and economic growth (SDG-8), and responsible consumption and production (SDG-12). Given the increasing amount of blade waste, circular economy business models are needed to support sustainable behaviour and supply clean energy.

CRediT authorship contribution statement

Peter Deeney: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualisation, Writing – original draft, Writing – review & editing. **Paul G. Leahy:** Conceptualisation, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Kevin Campbell:** Conceptualisation, Writing – original draft, Writing – reviewing & editing, Data curation. **Claire Ducourtieux:** Data curation. **Gerard Mullally:** Conceptualisation, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Niall P. Dunphy:** Conceptualisation, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Paul G. Leahy reports a relationship with BladeBridge Ltd. that includes: board membership and equity or stocks. Paul G. Leahy is an executive editor of Renewable & Sustainable Energy Reviews, he will be blinded during the review process and the manuscript will be handled by another editor. If there are other authors, they 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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Data availability

Datasets related to this article can be found at https://doi.org/10.5281/zenodo.10069849. Zenodo is an online data repository developed by the European OpenAIRE program [21].

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