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State-of-the-art review of product stewardship strategies for large composite wind turbine blades

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ABSTRACT

Is predicted that around 42 million tonnes of composite waste from wind turbine blades will need to be recycled annually worldwide by 2050. This poses a potential environmental crisis that must be timely mitigated. Therefore, this study proposes an integrated multilevel product stewardship to address the environmental impact of wind turbine blade waste. This product stewardship integrates circular economy, cleaner production, eco design, and industry 4.0 technologies. To tailor the proposed product stewardship, a systematic literature review that extracted a total of 267 studies and industry reports was performed. A large variety of technologies were identified under seven different potential pathways that can be taken and combined to address the environmental impact of wind turbine blades. Moreover, a technology roadmap and a project strategy plan composed of 5 milestones, to be achieved by 2050, were presented envisioning the maturation and adoption of the proposed solutions.

1. Introduction: challenges of composite wind turbine blades

1.1. Growth and impact of wind turbine energy generation

In 2021 the total amount of wind power installed globally reached approximately a total of 837.5 gigawatts which is mainly distributed amongst five countries China, USA, Germany, UK, and India (Lee and Zhao, 2022), as shown in Fig. 1. From the total amount of global wind power installed approximately 93% is onshore and 7% offshore (Fig. 1a and b). Among the current renewable energy sources, the growth of wind farms has been significant. According to the Global Wind Energy Council just in 2020 the growth of new wind power installations was 53% representing a total of 95.3 gigawatts (Fig. 1c) (Lee and Zhao, 2022).

Wind power uses the kinetic energy of the wind to produce a clean form of energy without producing contamination or emissions (Martínez et al., 2009). Despite the decline of 5% of global energy demand in 2020, renewables generated for the first time more electricity than fossil fuels (Lee and Zhao, 2021). Current forecasts predict that over 550 gigawatts of new wind power capacity will be installed by 2026 (Lee and Zhao, 2022) contributing to 2.64 million new jobs (Council, 2021). Moreover, by 2030, the cost of wind energy is anticipated to continue declining up to 55% from 2018 levels (Lee and Zhao, 2021) making this technology even more accessible (Wiser et al., 2016). In the EU alone, the binding target for increasing the renewable energy share is 27% by 2030, and the commitment is to cut greenhouse gas emissions by 80–95% by 2050 (Lee and Zhao, 2021). This emphasises wind power's important role in the future energy mix.

Nonetheless, when the whole life cycle of wind turbines is considered wind energy is not totally clean (Martínez et al., 2009). Contrary to other turbine components, composite wind blades have proven to be the sustainability blind spot of wind energy systems (Sakellariou, 2018). In terms of volume in 2016 the wind power industry used about 5.4 million tonnes of composite material, representing 6.8% of the total global composites market (Hakkı Hacıalioğlu, 2021), as shown in Fig. 1d. From an environmental point of view the disadvantage of common composite materials for wind turbine applications is their difficulty to be recycled. For each megawatt capacity of wind turbine installed 9.6 tonnes of

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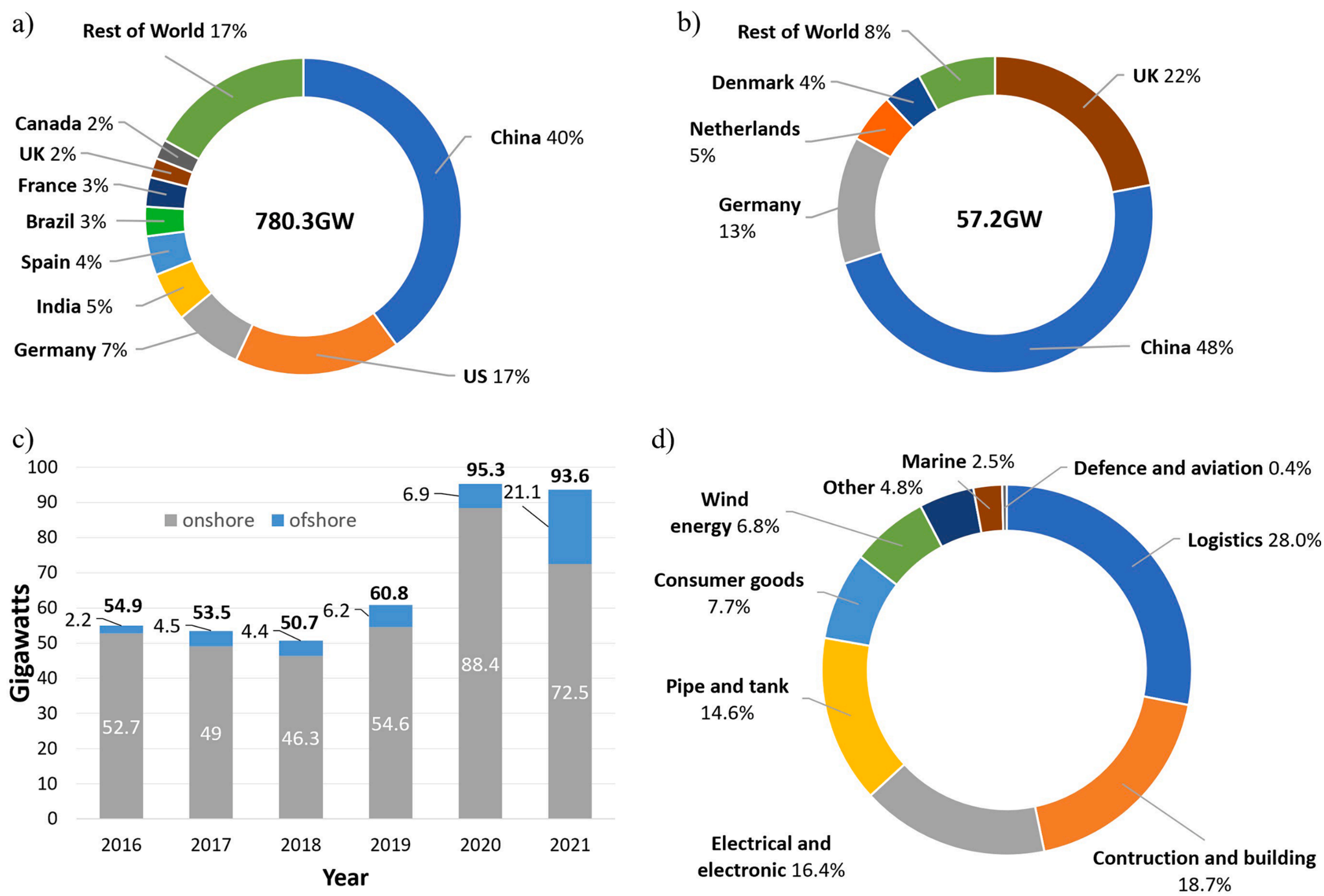

Fig. 1. (a) Distribution of total onshore wind power per country in 2021; (b) distribution of total offshore wind power per country in 2021; (c) New installations of global onshore and offshore wind power per year, adapted from (Lee and Zhao, 2022); (d) distribution of the global composites market by application in terms of volume in 2016, adapted from (Hakkı Hacıalioğlu, 2021).

composite materials are estimated to end up in landfills, contributing a massive amount of composite material to the waste stream (Arias, 2016). With a lifetime of 20–25 years for a wind turbine, it is predicted that around 42 million tonnes of rotor blade waste will need to be recycled annually worldwide by 2050 (Liu and Barlow, 2017).

This represents not only an environmental issue, but also a loss of potentially recoverable capital. The reason for this is that the end-of-life management of composite wind blades is a complex engineering problem that depends on the actual design of the blade, its material composition, the availability of recycling technology, legislation and requisite infrastructure, as well as the economics of the process itself, including the logistics of transportation, and dismantling, among other things (Sakellariou, 2018). Therefore, to maximize the environmental and economic benefits of wind power, sustainable recycling processes and alternative material solutions are needed to deal with wind turbines at the end of their service life.

1.2. Recent regulatory initiatives and challenges

1.2.1. China

The continued growth of wind power in China is mainly due to ambitious policies from the central government. For example, China's 14th Five-Year Plan published in 2021 was made to accelerate the development of renewable energy and reach the "30–60″ target (peak emissions by 2030 and carbon neutrality by 2060) on time (Lee and Zhao, 2022). According to the Global Wind Energy Council (GWEC 2020) "*An industrial development plan of this scale would bring China's cumulative wind capacity to at least 800 GW by 2030 and 3000 GW by 2060, in line with the long-term carbon neutrality goal*".

Despite China being the world leader in wind energy since 2010, their wind power sector 15 years ago was only 0.2 Megawatts (Yang et al., 2017). In terms of WTB waste this means that by the year 2031 the first batch of WTB waste will by approximately 60 tonnes (Association ANM, 2020). However, the accumulative WTB waste that will be generated in China between the years 2035 and 2044 will be about 74, 000 tonnes (Akbar and Liew, 2020). Unfortunately, in China landfill (36%) is the main method to deal with plastics in China with only 14% of plastic waste been incinerated, 30% recycled, and the remaining 20% been dumped into the environment (Wang et al., 2021). As a result, China ranks the world's top polluter with mismanaged plastic waste in the world, leaking an estimated 3.53 million metric tonnes of plastic wastes into the oceans (Jambeck et al., 2015).

To deal with their solid waste problem, China in resent have been introducing several strategic plans and heavily investing in waste-to-energy technologies. For example, between 2016 and 2020 China's 13th Five Year Plan aimed to keep the circular economy and low–carbon economy as focus areas by targeting a 90% treatment rate for domestic waste in rural areas and 73% reuse rate for industrial solid waste by 2020 (Circular, 2022). Moreover, the plan also introduced binding targets relevant for the circular economy, emphasizing the importance of an Extended Producer Responsibility (EPR) framework, and proposing to further strengthen municipal waste management and the remanufacturing industry (Circular, 2022). Later in 2018, China launched "National Sword" policy where the import of most plastics and other materials where banded, only allowing the entrance of plastic materials with a 99.5% purity standard (Yoshida, 2022). Then at the beginning of

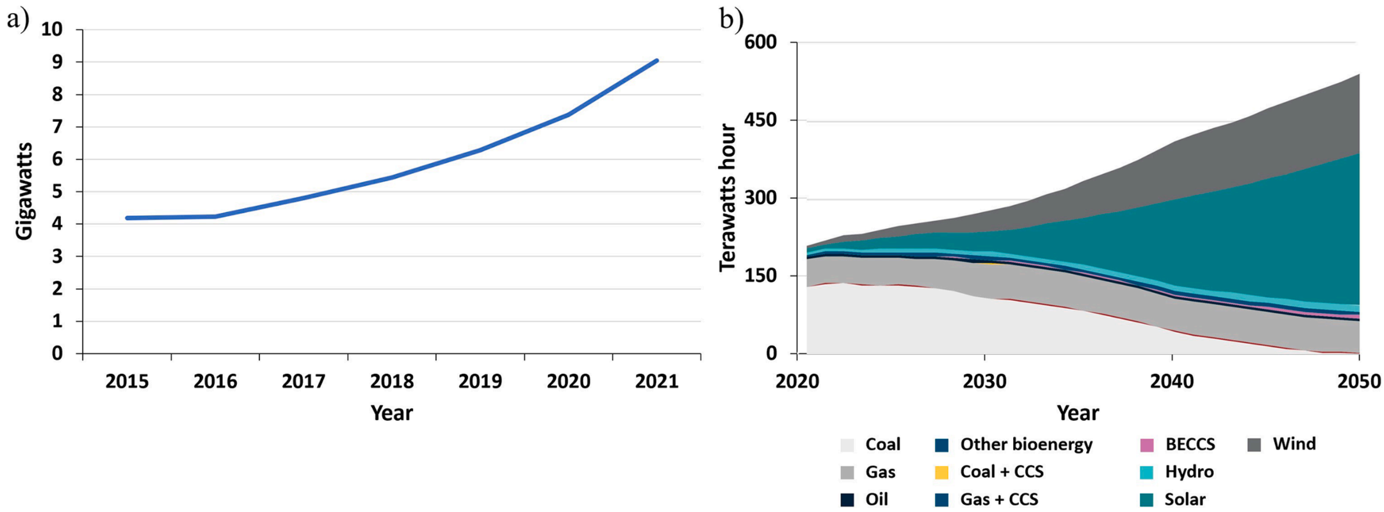

Fig. 2. (a) Cumulative installed capacity of wind power in Australia (Council, 2021); (b) Australia's electricity generation plan 2020 – 2050 (DISER 2021).

2020 the Chinese National Development and Reform Commission and the Ministry of Ecology and Environment proposed to further strengthen the guidance of innovation and the support of science and technology to control plastic pollution, and promote the standardization, centralization, and industrialization of the resource utilization (Wang et al., 2021).

China's main technological strategy to reduce their solid waste has been by investing in waste-to-energy technologies such as fluidized bed combustion (Kurniawan et al., 2022). Currently, China is the country with the largest installed waste-to-energy capacity of any country, with more than 300 plants in operation (Wang et al., 2021). In less than 20 years, China's waste-to-energy incineration plants capacity grew from 3.70 to 133.08 million metric tons (Cui et al., 2020). For example, recently in Urumqi, capital of northwest China's Xinjiang it was put into operation a mega waste-to-energy plant that is expected to treat 1.2 million tonnes of solid waste per year reducing coal consumption by 500,000 tonnes per year (news, 2021). Moreover, the Shenzhen East waste-to-energy project will be the world's largest waste-to-energy power plant designed to combust 5600 tonnes of solid waste per day and produce 165 Megawatts of electricity (Energy, 2021).

1.2.2. *European Union*

In 2015, the European Commission officially adopted a European Union (EU) plan aimed at the establishment of a circular economy (CE) to cope with Earth's limited natural resources by focusing on resource efficiency and the decoupling of economic growth from resource consumption (Sommer et al., 2020). One of the main points of this strategy is the management of plastics through their entire life cycle to ensure their recyclability (Commission, 2018). In line with this, the EU directive on waste states that once a product becomes waste, the preferred waste management strategy is reuse first, followed by recycling, recovery, and disposal (Council, 2018). However, this strategy mainly concerns single-use plastics (packaging, microplastics, and oxo-plastics), leaving only a few regulatory requirements for the composite sector (Commission, 2018). One of the reasons is that in most EU countries, composite blade waste is most often categorised as plastic waste from construction and demolition (Schmid et al., 2020).

The EU Directive on Landfill Waste currently prohibits the disposal of large composite parts such as WTB (Cousins et al., 2019). This leads to most European countries resorting to other waste management strategies such as incineration (Overcash et al., 2017). However, composite materials are forbidden from being landfilled or incinerated in Germany, Austria, the Netherlands, and Finland (Schmid et al., 2020). Additionally, France is planning the introduction of a recycling target for wind turbines in its regulatory framework (Ecologique, 2020). The leadership of these countries will likely lead to an increase in landfill taxes and limited capacity, making landfilling and incineration unacceptable future solutions in the EU (Ribeiro et al., 2015). For example, one of the EU's current targets for waste reduction is a binding landfill goal to reduce landfilling to a maximum of 10% of municipal waste by 2030 (European Commision 2020). As a result, the European composites industry is facing growing environmental pressures.

1.2.3. *United States*

Nonetheless, the regulatory scenario in the US is completely different compared with the EU. In the US, landfilling of large composite materials is the most common route of disposal due to the lack of regulations and the cost efficiency of this alternative (Ramirez-Tejeda et al., 2017). In 2008, the US Energy Department released the US wind energy plan in a report called "20% of the nation's electricity demand by 2030" (Energy, 2008). According to Wilburn (Wilburn, 2011), to reach the goal of this proposed wind energy plan, the US will require between 2.3 million and 2.7 million tonnes of composite material, which does not include the current wind turbines already installed. Unfortunately, the US Energy Department report did not include plans considering the management of the composite waste that will be generated at the end of the WTBs' life cycle (Energy, 2008). However, despite discouragement in the US regarding the reduction of composite waste, the American Composites Manufacturing Association (ACMA) has taken some critical steps to promote recycling. The ACMA recently produced a report called "Wind Turbine Blade Recycling: Preliminary Assessment" to mainly explore the different recycling technology possibilities, site location considerations, and techno-economic analysis models for the US (Association, 2020). According to this report, by the end of 2050, there will be approximately 4 million tonnes of blade waste. Some of the key findings presented in the report are as follows: (1) mechanical recycling faces economic and market challenges, including a current lack of high-value end-use applications; cement kilns are more sustainable but currently cost about twice as much as solid waste disposal; pyrolysis offers attractive economics for the recovery of CF, but it requires technological development and a high initial investment; and there is a need for the collaborative development of commercial-scale facilities for front-end processing of composite scrap (Association, 2020).

According to Ramirez-Tejeda et al. (2017), the growth of the wind turbine blade (WTB) recycling industry in the US depends on different governmental initiatives that need to be in place. For example, a combination of policy interventions with tax breaks and subsidies can encourage the growth of existing recycling companies and the creation of new ones. This can be done by prohibiting or imposing a tax on landfilling practices to stimulate the recycling of composite materials

(Ramirez-Tejeda et al., 2017); this strategy was also identified by the ACMA (Overcash et al., 2017). Additionally, the implementation of governmental tax breaks and subsidies for the recycling industry can help to reduce operational costs, thereby allowing the recycling industry to offer more competitive prices (Ramirez-Tejeda et al., 2017). Nonetheless, the current situation in the US regarding the proper management of WTB waste mainly depends on close collaboration between industry, research institutions, and national and federal governments, as well as pressure from the public to adopt environmentally sound practices.

1.2.4. Australia

In Australia, wind power is currently the cheapest source of large-scale renewable energy. As a result, the Australian installed wind generation capacity has been steadily growing since 2016 moving from 4181 to 9041 megawatts in 2021, as shown in Fig. 2a (Council, 2021). Since 2019, wind has been Australia's leading source of clean energy, representing 35.9% of the Australia's clean energy and 9.9% of the country's total electricity in 2020 (Council, 2021). The Australian Government has identified wind energy as one of the priority technologies for their Long-Term Emissions Reduction Plan to deliver net zero emissions by 2050 (DISER 2021). The Australian Government's approach is to unlock investment and accelerate technology deployment by removing barriers such as taxes and providing incentives and finance for firms to deploy wind energy technologies (DISER 2021). According to the Australian Department of Industry, Science, Energy and Resources (DISER 2021), by 2050 wind power will be the second highest energy generator after solar representing approximately 28% of all Australian energy generated, as shown in Fig. 2b (DISER 2021).

Nonetheless, despite the Australian Government's efforts to encourage investment in wind power, there are no current plans for the management of waste generated from WTBs (Redlich, 2021). Unfortunately, Australia does not have large scale facilities for recycling carbon fibre and fibreglass composites suitable for (Freeman, 2020) and the Government considers that carbon taxes are regressive, with significant costs borne (DISER 2021). Currently in Australia, there are about 101 wind farms from which 15% are over 15 years old, with only two farms being 20 years or older (Freeman, 2020). Hence, if we estimate the composite waste which will be generated when the decommissioning of wind turbines will start, then according to the present installed capacity of Australia which is about 9041 megawatts, a total 86,794 tonnes of composite waste will be accumulated.

1.3. A need for a holistic environmental management approach

The increasing pressure from governments to adopt green manufacturing practices with tax benefits and environmental regulations is leading companies to economically justify sustainable manufacturing practices (Deif, 2011; Yusup et al., 2013). For designers and producers of WTBs, this means to take responsibility for finding ways to design and produce blades that require fewer harmful substances and that are more durable, reusable, and recyclable (Consoli, 1993; Knight and Jenkins, 2009; Ratner et al., 2020; Piasecka et al., 2020). However, green manufacturing practices are mainly concerned with product life cycles up to and including the manufacturing step (Rosselot and Allen, 2002). Moreover, some of the existing waste management frameworks do not offer a complete holistic approach to address WTB waste from environmental, economic, and social perspectives (Papargyropoulou et al., 2014). This creates a disruption to the environmental efforts in the product life cycle. Therefore, umbrella product management approaches such as product stewardship are needed to integrate different strategies as cleaner production and circular economy (CE) (Jensen and Remmen, 2017). This can bring benefits to the wind turbine industry that overlap with business performance by simultaneously increasing profitability, efficiency, competitiveness, and environmental performance.

Product stewardship is a management strategy aimed at the reduction of products' negative impact on the environment by maximising their value (Saxena et al., 2018). Product stewardship includes the entire life cycle of products, from the cradle to the grave, to ensure that they are safe as well as socially and environmentally responsible (Mbabazi et al., 2020; Lane and Watson, 2012; Dufrene et al., 2013; Lewis, 2006; Stitzhal, 2011; Sihvonen and Partanen, 2017). For this purpose, product stewardship uses a multi-stakeholder approach that involves the participation of all actors, including the producer, manufacturer, importer, distributor, retailer, consumer, and recycler (Sheehan and Spiegelman, 2006). However, to implement product stewardship it is required to create new industry standards, regulations, and governmental policies to facilitate a fair distribution of responsibility among all players and to find the most workable and cost-effective solutions (Nicol and Thompson, 2007). These new industry standards, regulations, and governmental policies should be just, tolerant, and equitable; take into account the interests of all concerned; and avoid bias in the distribution of benefits and burdens among those in present and future generations (Welchman, 2012).

One of the most well-known green manufacturing practices is called cleaner production which is also known by a variety of different names, including sustainable manufacturing, environmentally benign manufacturing, and green manufacturing to name a few (Sangwan and Mittal, 2015). Cleaner production is a full life cycle product strategy and powerful company-specific environmental protection initiative that aims for efficient use of natural resources, reduction pollution (Maruthi and Rashmi, 2015). Moreover, the implementation of cleaner production also aims for the careful selection of environmentally friendly technologies and adequate process design with minimum waste disposal represents significant cost savings and more market competitiveness (Yusup et al., 2013; Giannetti et al., 2008).

Another management approach that aims for the efficient use of resources is circular economy (CE) (Lane and Watson, 2012). Circular economy goal is to close material loops within economic systems by integrating business models and sustainable manufacturing systems to increase resource efficiency (Boulding, 1992; Ghisellini et al., 2016). Thus, resources can be used for as long as possible by extracting the maximum value of materials through efficient material recovery systems to generate new products and applications (Mrowiec, 2018). The concept of a CE has been gaining traction thanks to its promotion by several governments and international organisations, for example the EU's 'Zero waste programme for Europe' and Japan's 'material-cycle society vision' (Van Eygen et al., 2018; Huysman et al., 2017). Nonetheless, to achieve a true CE it is necessary to fully embrace Industry 4.0.

Industry 4.0 refers to the fourth industrial revolution, fuelled by nine foundational technological advances (Rüßmann et al., 2015): big data analytics, autonomous robots, simulation, horizontal and vertical system integration, the Internet of Things, cybersecurity, cloud computing, augmented reality, and additive manufacturing (AM) (Rüßmann et al., 2015; Hermann et al., 2016). This predicted industrial revolution promises social, economic, and political changes by forging a new pathway to facilitate the multi-stakeholder approach of product stewardship towards CE and cleaner production strategies. All this is possible through the establishment of sustainable smart factories, extend the life of products, and digitally track the material flow across the materials' different life cycles in the products in which they are used (Rojko, 2017; Stock and Seliger, 2016; Lasi et al., 2014).

2. Purpose and objectives

Taking into consideration the need for the development of high-level management strategies to initiate global collaboration to ultimately avoid the potential environmental crisis triggered by the waste of WTB. This study proposes an integrated product stewardship approach for WTB. This strategy is aimed to set the foundations for a global environmental collaboration to binding together all the different actors, stakeholders, economic and technological factors to address the environmental challenge of WTB. Hence, the current study sought to achieve the following four main objectives:

1) Present an umbrella product stewardship to integrate circular economy (CE), cleaner production, eco design, and industry 4.0 technologies.
2) Present the different potential product stewardship strategies and pathways that can be taken to address the environmental impact of WTB.
3) Identify the TRL of potential technologies and present a technology roadmap of the pathways that can be taken to address the environmental impact of WTB.
4) Present a project plan and strategies to direct the maturation and adoption of solutions to address the environmental impact of WTB.

3. Materials and methods

This is a qualitative exploratory research study that is focused on proposing a multilevel product stewardship to address the environmental impact of WTB. For this purpose we employed a constructive research approach which is aims to produce innovative solutions to practical problems in a heuristic manner (Oyegoke, 2011). The solutions are commonly proposed using managerial problem-solving techniques through the construction of models, diagrams, plans, and organizations (Kasanen et al., 1993). The recommended solutions require the researchers to immerse themselves in the contextual literature to allow an in-depth interpretation and synthesis of the problems (Oyegoke, 2011).

3.1. Data collection (Link this with the objectives)

Two systematic searches were conducted on the 20th of November and 27th of August of 2020 using the *Science Direct* and *Google Scholar* databases following the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement (Liberati et al., 2009). In the first systematic literature search, based on the objective 1 of this study, was performed with the keywords ‘wind turbine*’, ‘wind blade*’ connected with the Boolean operator ‘“OR”’ and accompanied by the following keywords using the ‘“AND”’ Boolean operator: ‘health monitoring’, ‘material*’, ‘fabrication’, ‘manufactur*’, ‘refurbish*’, ‘remanufact*’, ‘repurpos*’, ‘recycl*’, ‘prevent*’, ‘recover*’, ‘dispos*’.

Three full phrase used for the first search was:

> (‘wind turbine’ OR ‘wind blade’) AND (health monitoring’ OR ‘material’ OR ‘fabrication’OR ‘manufactur’ OR ‘refurbish’ OR ‘remanufact’ OR ‘repurpos’ OR ‘recycl’ OR ‘prevention’ OR ‘recover’ OR ‘dispos’)

The second systematic search was performed to achieve the second objective of this study using the keywords ‘wind turbine*’, ‘wind blade*’ connected with the Boolean operator ‘“OR”’ and accompanied by the following keywords using the ‘“AND”’ Boolean operator: ‘TRL’, ‘technology readiness level’, ‘incineration’, ‘co-incineration’, ‘cement kiln’, ‘kiln’, ‘microwave pyrolysis’, ‘pyrolysis’, ‘fluidised bed’, ‘solvolysis’, ‘high voltage fragmentation’, ‘repurpos’, ‘remanufactur’, ‘refurbish’, ‘additive manufactur’, ‘3D print’, ‘thermoplastic*’, ‘hybrid fibre composite’, ‘vitrimers’, ‘reversible thermosetting’, ‘self-healing’, ‘nano’, ‘additive’, ‘health monitor’, ‘circular design’, ‘eco design’, ‘generative design’, ‘digital twin’, ‘smart manufactur’.

Three full phrase used for the second search was:

> (‘wind turbine’ OR ‘wind blade’) AND (‘incineration’ OR ‘co-incineration’ OR ‘cement kiln’ OR ‘kiln’ OR ‘microwave pyrolysis’ OR ‘pyrolysis’ OR ‘fluidised bed’ OR ‘solvolysis’ OR ‘high voltage fragmentation’ OR ‘repurpos’ OR ‘remanufactur’ OR ‘refurbish’ OR ‘additive manufactur’ OR ‘3D print’ OR ‘thermoplastic’ OR ‘hybrid fibre composite’ OR ‘natural fibre” OR ‘vitrimers’ OR ‘reversible thermosetting’ OR ‘self-healing’ OR ‘nano’ OR ‘additive’ OR ‘health monitor’ OR ‘circular design’ OR ‘eco design’ OR ‘generative design’ OR ‘digital twin’ OR ‘smart manufactur’) AND (‘TRL’ OR ‘technology readiness level’)

Table 1
Search strategy, custom range 2000–2021.

Data base	Records identified	Total
Google Scholar	872,500	959,131
Science Direct	86,631	
Duplicates	61,920	897,211

3.2. Selection criteria

The initial literature search returned a total of 959,131 articles from which a total of 61,920 duplicated articles were removed, as presented in Table 1. The remaining articles were screened to determine whether they met the following inclusion criteria: (1) conference and peer-reviewed papers with the full-text published within the last 20 years (2000 – 2021), (2) empirical studies on WTBs and related technologies, and (3) published in the English language. We assessed the first 10 pages of each of the search results per search phrase and sorted the search results by relevance. The screening process was performed on 350 articles, from which a total of 263 articles were full-text assessed for eligibility. In the eligibility process, articles that were not related to WTBs and associated technologies were excluded. At the end of the study selection process, 267 (239 research articles and 28 industry and government reports) were determined to meet the inclusion criteria for this review, and as shown in Fig. 3.

3.3. Data extraction and analysis

The systematic literature searches aimed to identify the different potential technologies and their corresponding technology readiness level to address the environmental impact of WTB. The classification topics were as follows: year, location, prevention, reduction, refurbish/remanufacture, repurpose, recycling, recovery, and disposal. Full-text screening was performed by D.M. and R.A.S.to avoid potential bias. A consensus meeting resolved any discrepancies between reviewers. Once all applicable literature was identified, the extracted data was analysed the product stewardship framework for composite WTBs was formulated.

4. Results: product stewardship strategies

An initial data classification was performed as described previously (see Table A1 in Appendix A). After this, a more detailed analysis was performed in which a total of 2240 qualitative data items were extracted and synthesized to tailor an integrated multilevel product stewardship and a technology road plan to address the environmental impact of WTB waste. The resulting proposed multilevel approach is composed of 11 hierarchical levels that represent 11 different factors that complement each other.

At the highest level, product stewardship, acts as an engineering management umbrella that integrates the remaining hierarchical levels. The second level is CE representing the economic factor that makes possible the viable the closed-loop of production and consumption of natural resources. At the third level are the design and manufacturing factors (eco-design and cleaner production) that allow the design and production of green WTB. The fourth level is the technological and digital factor which is composed by Industry 4.0 technologies that act as the digital engine to run the three levels above. The remaining seven hierarchical levels represent the different pathways to address the environmental impact of WTB. These seven pathways are based on a 5Rs

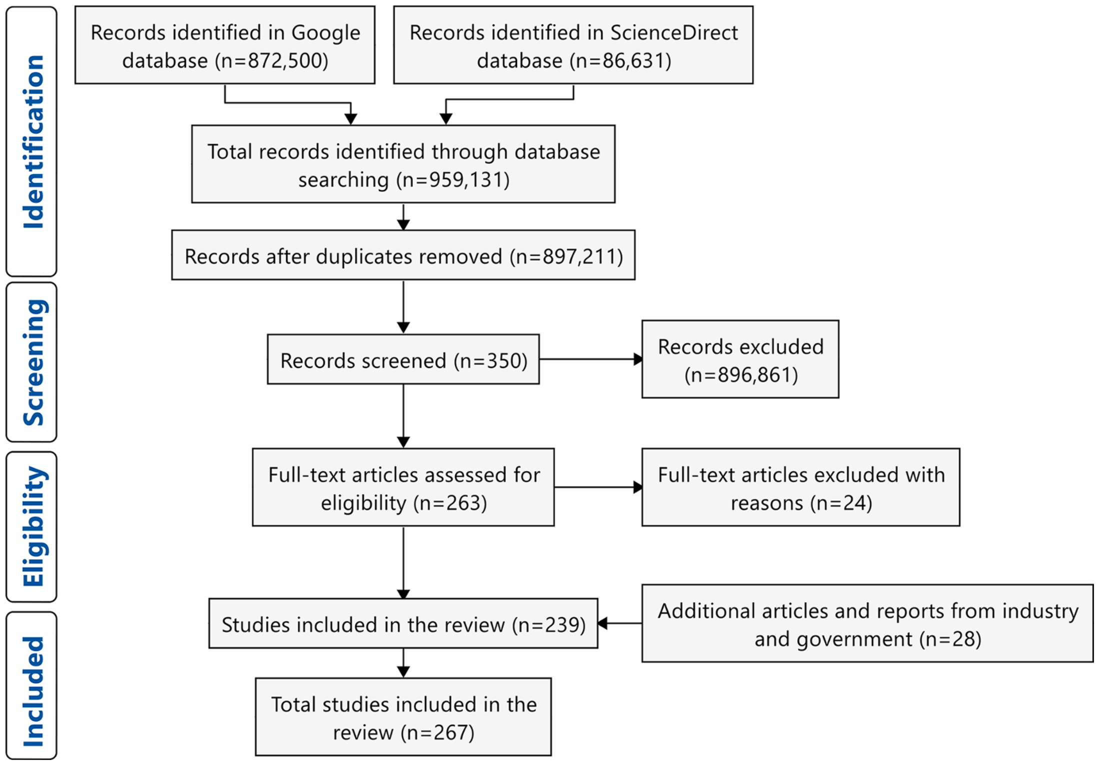

Fig. 3. Search strategy and study selection.

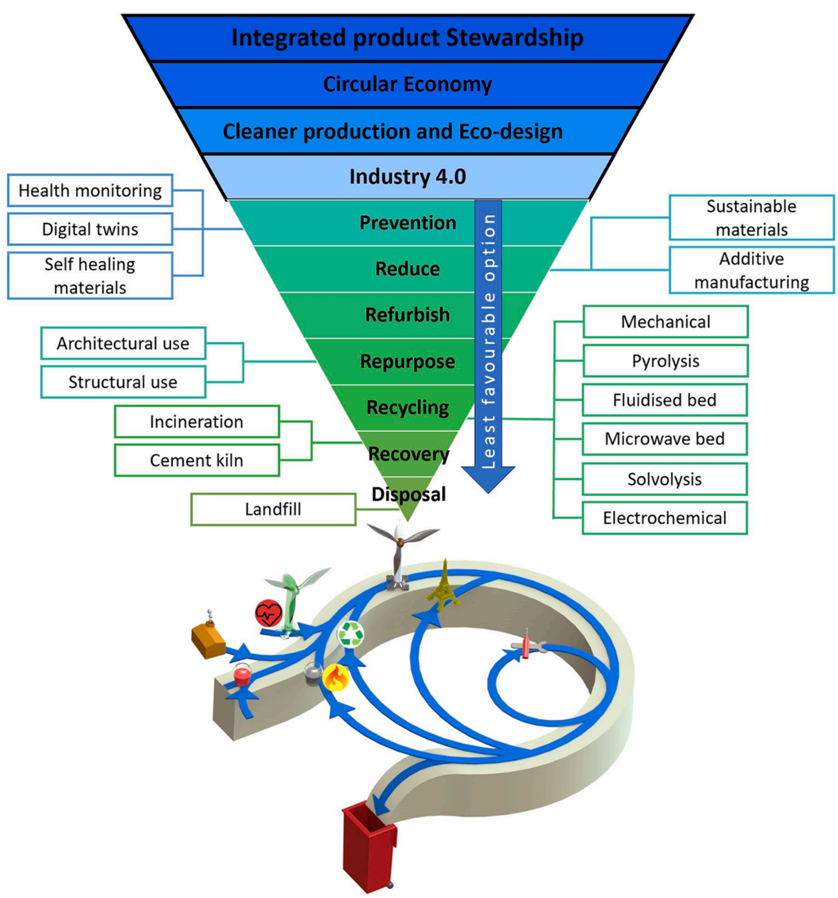

Fig. 4. Integrated multilevel product stewardship framework for wind turbine blades embracing circular economy, cleaner product/Eco design, Industry 4.0, and the 5Rs waste management hierarchy, adapted from (Papargyropoulou et al., 2014).

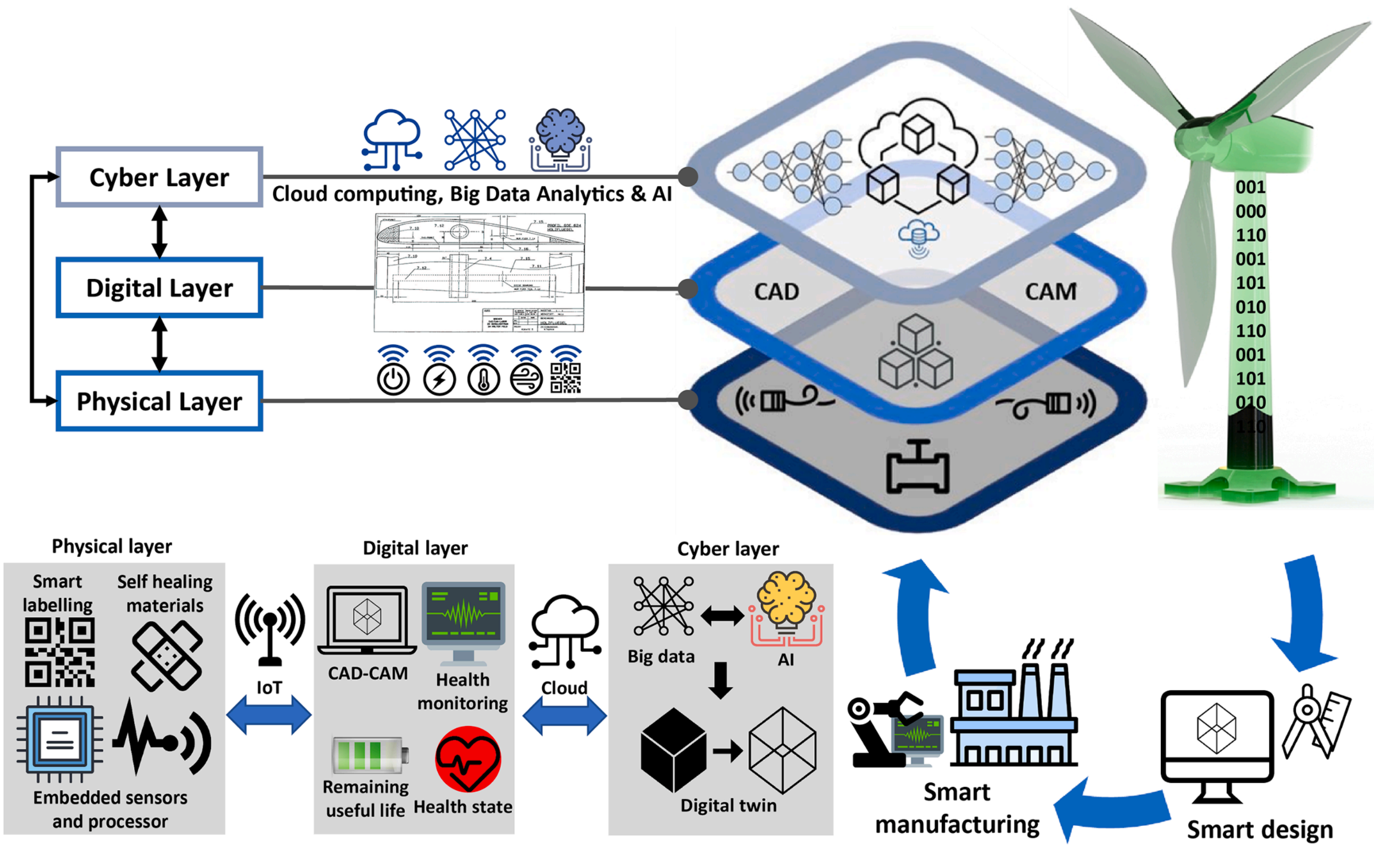

Fig. 5. Conceptual digital twin reference model for wind turbines, adapted from (Aheleroff et al., 2021).

waste hierarchy (prevention, reduce, refurbish, repurpose, recycling, recovery, and disposal), as shown in Fig. 4.

A large variety of potential technological solutions were identified to drive the wind energy industry towards more environmentally sustainable practices. Some of these solutions come from the engineering side, the development of novel materials, and implementation recycling technologies to name a few. According to the waste management hierarchy sustainable development and resource efficiency can be achieved using a top-down strategy. The main goal of the waste hierarchy is to facilitate the selection of the options most likely to deliver the best overall environmental outcome (Schmid et al., 2020). Therefore, the proposed 5Rs waste hierarchy serves as template to present different potential opportunities to overcome the potential environmental crisis that can result from the incoming waste generated by the disposal of WTB. The following sections of this manuscript provide a description of the different pathways and technologies that can be taken and combined within the proposed integrated multilevel product stewardship for WTB.

4.1. Prevention strategies

According to Gharfalkar et al. (2015) prevention strategies consist of the measures taken before a substance, material or product has become waste in order to prevent waste generation. In the case of WTB prevention strategies should focus on the life extension of blades as well as the optimisation of their design and manufacturing processes. Better design strategies can help to replace non-renewable resources with renewable resources. The optimization of manufacturing processes can allow to produce WTB using less resources and avoiding production waste. The life extension of WTB could prevent disposal of blade composite material for several years opening a window of opportunity for industry to move into environmentally friendly alternatives. However, to unleash the full potential of waste prevention strategies and achieve high levels of efficiency and sustainability it is imperative to link all the aspects of the lifecycle of WTB. This may require converging the physical and cyberspace through an appropriate flow and use of data of both worlds (Tao et al., 2018). For this purpose, Industry 4.0 technologies such as structural health monitoring, digital twin, and self-healing materials need to be integrated.

4.1.1. An integrated digital twin for wind turbine blades life cycle

According to Güemes et al. (2020), in the last 20 years, little progress has been made in relation to sensor development for SHM systems. However, the declining costs of computing and communication technologies, as well as algorithm improvements, have paved the way for the integration of robust SHM systems with building information modelling (BIM) into the creation of digital twins of built assets, machines, and systems (Theiler et al., 2017).

BIM systems are widely used in the architecture, engineering, and construction industries to create a precise 3D representation of a building containing relevant data to support the management of the building through its entire life cycle, from design and procurement to fabrication, construction, and maintenance (Azhar, 2011). One of the most important characteristics of BIM is visualisation. BIM uses 3D virtual environments to facilitate the real-time analysis and visualisation of different details, such as cost, material properties, inventories, and geographical information, to demonstrate the entire building's life cycle (Wang et al., 2018). In contrast, a digital twin is an extension of BIM integrated with real-time SHM to create dynamic digital clones of machines and systems to update the status of their physical counterparts and mirror almost every facet to monitor and predict their behaviour (Lu et al., 2019; Pan and Zhang, 2021; Erikstad, 2017). For this purpose, the creation of digital twins requires multiphysics, multiscale, probabilistic approaches to produce an ultra-fidelity simulation of a physical model (Tao et al., 2019).

The purpose of a digital twin for WTB lies in creating a virtual model of their physical appearance, functionality, and characteristics to understand, predict, estimate, and analyse and manage their life cycle. With the combination of Internet of Things (IoT), Big Data Analytics, Cloud Computing, and Artificial Intelligence (AI) different aspects of the life cycle of WTB can be integrated. For industrial purposes such as the life cycle of WTB. Aheleroff et al. (2021) described that a digital twin should be composed of four different layers Physical layer, Digital layer, and Cyber layer. The fourth layer is the Communication layer that connects the other three layers for data exchange to carry real-time data as a mapping between selected physical elements and their digital model and process in cyberspace, as illustrated in Fig. 5.

The first aspect of a digital life cycle starts with the creation of a digital twin of the WTB. The application of digital twins for WTB can facilitate their design, fault diagnosis, maintenance, and life cycle management. For this purpose, smart labelling, structural health monitoring systems, IoT, machine learning/artificial intelligence will need to be integrated to create an accurate copy of the physical system. The implementation of smart labelling and embedding information into the blade will help to cover aspects such as the material type, source, and state of the materials (if they are new or recycled), and other pertinent information to facilitate their repurpose recycling, and recovering (Condemi et al., 2019). This will allow the future creation of a multi-life-cycle management process of FRPC (Wang et al., 2020).

During the fabrication process different types of structural health monitoring systems and other type sensors to track environmental conditions such as wind speed, wind direction, temperature, humidity, and pressure can be imbedded withing the critical sections of the wind turbine (Tao and Qi, 2019; Pimenta et al., 2020). The data obtained through structural health monitoring systems can be used to monitor in real-time and predict the current and future condition of the WTB. Moreover, all the valuable information obtained through the digital twin of the WTB can be used as feedback to product design to optimize the blade, test new design approaches or to simulate new materials (Kaur et al., 2019; Tao et al., 2019). Additionally, digital twins can reduce the access challenges and risks frequently encountered in offshore wind turbines. Furthermore, the data obtained from a WTB digital twin can also be integrated with a digital twin of the manufacturing process for the optimization of the whole manufacturing process to create intelligent greener manufacturing processes through the identification of bottlenecks, and the causes and impacts of the problems (Qi and Tao, 2018).

4.1.2. *Structural health monitoring*

Wind turbines have high operation and maintenance costs, accounting for 20–25% of the total levelized cost per kWh over the lifetime of a turbine (Morthorst, 2021). In the case of WTB, a new blade can cost $200,000 on average, and structural repair can cost up to $30,000 per blade (Stephenson, 2011). However, the total cost incurred in blade incidents per wind turbine can be approximately $1 million (GCube 2014). During the 20–30 years of life of a wind turbine, 19.4% of its failure is attributed to the blades, whose three main damage causes are lightning, storms, and strong winds (Chou et al., 2013). In addition, some of the typical physical mechanisms of WTB degradation and failure are surface erosion, fibre failure, adhesive fatigue, delamination, compressive kinking, and laminate cracking (McGugan and Mishnaevsky, 2020).

In the last two decades, different types of structural health monitoring (SHM) systems have been implemented and successfully demonstrated on large-scale engineering structures in the aviation, construction, and wind turbine industries (McGugan and Mishnaevsky, 2020; Gatti, 2019; Gómez et al., 2020; Diamanti and Soutis, 2010). The main purpose of SHM is to extend the life of WTB and reduce maintenance cost by identifying material damage before it causes catastrophic incidents (Du et al., 2020). The main advantage of SHM systems over preventive maintenance methods is that they can evaluate the structural

Table 2
Working principle, advantages and limitations of different damage detection methods used in SHM (Güemes et al., 2020; McGugan and Mishnaevsky, 2020; Du et al., 2020; Ciang et al., 2008; Li et al., 2015; Schubel et al., 2013; Rizk et al., 2020).

Damage detection method	Working principle	Advantages	Limitations
Acoustic emission	Uses piezo metric sensors to detect the stress waves created by the blade's material stress release process during failure.	• Mid-range. • It can detect micro-structural material changes such as cracking, delamination, and fatigue. • Can assess the damage severity. • It can determine the location of damage points. • Rapid and efficient • Non-invasive • Real-time monitoring.	• Demands large number of sensors. • Requires data acquisition system with high sampling frequencies. • Signal processing is complicated. • Cannot provide information about the material internal structural stress. • High cost
Thermal imaging	Infrared sensors or cameras are used to detect temperature differences caused by subsurface defects in the material to identify material irregularities or damage.	• Global range. • It can measure surface stress distribution, size of cracks. • It can identify stress concentrations, invisible sub-surface damage, root delamination, and trailing-edge cracks, thermal damage. • It can be used to evaluate bonding quality and entrapped air. • Produces a full-field measurement in image form.	• For wind turbine blade applications requires an external stimulus source. • Limited application for on-line monitoring • Can be affected by the environment conditions.
Ultrasonic methods	Uses ultrasound waves to identify material defects that are orientated perpendicular to the direction of sound wave propagation	• Mid-range. • It detects material damage small as few milometers, delamination, cracks, and interlaminar weakness. • It can identify location and the severity of the damage. • It is efficient and reliable. • Can provide a scanned movie or snapshots of the structural damage.	• Only can detect defects that are orientated perpendicular to the direction of sound wave propagation. • Cannot detect single fibre rupture. • Requires surface contact and long acquisition time. • Signal processing is complicated
Modal-based	It detects changes in the material physical properties using modal parameters such as frequencies, mode shapes and modal damping.	• Global and local range. • It can accurately predict the location of local damage. • Is easy to implement.	• Requires data from healthy material regions to be compared with damaged areas. • It is not easy to extract local information caused by small damage. • Unable to monitor early damages.

(continued on next page)

Table 2 (*continued*)

Damage detection method	Working principle	Advantages	Limitations
			• Can be affected by the environment conditions.
Fibre optics	Uses optical fibres to sense material strain	• Mid-range. • Short length optical fibre can be embedded in the composite material during fabrication. • Real-time detection of early damage, traverse crack evolution, and impact damage. • On-site calibration is not required. • Can simultaneously read large numbers of sensors on a very few fibres, leading to reduced cabling requirements and easier installation. • Can monitor strain and temperature simultaneously. • Automatic. • High sensitivity. • Can be used for lifetime prediction. • Long term stability under operation in hostile environments • Competitive costs	• Fragile • The data acquisition unit is expensive and bulky. • Requires prior knowledge about high strain areas. • Requires large amounts of sensors
Laser Doppler vibrometer	Uses a non-contact velocity transducer, based on the analysis of the Doppler effect on a laser beam to detect changes in the modal properties of the material	• Global range. • Non-contacting capabilities. • Easy implementation • Is automatic. • High sensitivity. • High spatial resolution of measurement. • Good damage detection accuracy. • An image or movie be obtained for damage evaluation	• Requires massive number of sensors. • Expensive
Electrical resistance-based damage detection	Uses the conductive property of the carbon fibres to measure electrical resistance changes in the material.	• It can detect fatigue damage, matrix cracking, delamination, and fibre breakage. • It can determine the location and size of damaged areas.	• Local range. • It can only be used with carbon fibre reinforced composites.
Traditional strain gauges	Use electrical sensor that are sensitive to a differing electrical property.	• Global range. • Can detect microscopic material changes. • Does not require external power.	• Requires large amounts of sensors. • Prone to failure • Measure only point strain. • Requires prior knowledge about high strain areas
Smart memory alloy strain gauges	Uses the changing magnetic susceptibility of smart memory alloy sensors to measure the strain experienced by the composite material	• Global range. • Sensors can be embedded in the composite material during fabrication. • Does not require external power	• Expensive • Labour intensive.
X-radioscopy	Uses X-rays to obtain images of the material surface and interior	• Data collection can be done using non-contact susceptibility sensors. • It can detect missing cracks, voids, and missing glue between laminates, as well as non-intended orientation of fibres. • Enables detection of defects less than 10 μm.	• Local range. • Cannot reveal cracks orientated parallel to the X-rays. • Require shielding and/or proper safety distances.
Eddy current	Induces electrical currents in the test material and records variations of the induced currents to detect material changes.	• It can detect surface and subsurface defects. • Has good deep defect detectability. • High reliability. • Good defect visibility.	• Local range. • It can only be used with carbon fibre reinforced composites. • Difficult to be applied in-service WTB. • Requires prior knowledge of damage location. • damage detection and localization possible • It can detect surface and subsurface defects
Computer vision	Uses binocular vision detection methods to obtain sequences of 2-dimensional/3-dimensional images to obtain information of the target object.	• Global range. • Suitable for on-line monitoring • Detection of surface damage • High detection accuracy and efficiency. • Low cost	• Only detect visible external damages. • High requirements on imaging devices and data processing capabilities.

condition of WTB in a minimally disruptive manner (Solimine et al., 2020). Moreover, SHM systems can help to identify the location and root cause of material damage (Kusiak et al., 2013). Damage detection methods used in SHM are mainly based on thermography, sound wave propagation, electrical resistance, laser, and strain measurement, among others (Ciang et al., 2008). Depending on the damage detection method employed, SHM can be used for early warning, problem identification, and continuous monitoring (Hameed et al., 2009).

The advantages and disadvantages of the different detection methods employed for SHM mainly depend on the type of sensors and the working principle used to detect structural failures; details of these methods are presented in Table 2. Furthermore, SHM systems can be classified as either active or passive: active systems (e.g., laser doppler vibrometer) require an external power supply, whereas passive systems (e.g., smart memory alloy strain gauges) do not (Ciang et al., 2008). SHM systems can also be distinguished according to their sensing range as either local or global: local systems are limited to the area under the sensor, whereas global systems can detect damage in any location in the structure by a network of sensors (Güemes et al., 2020).

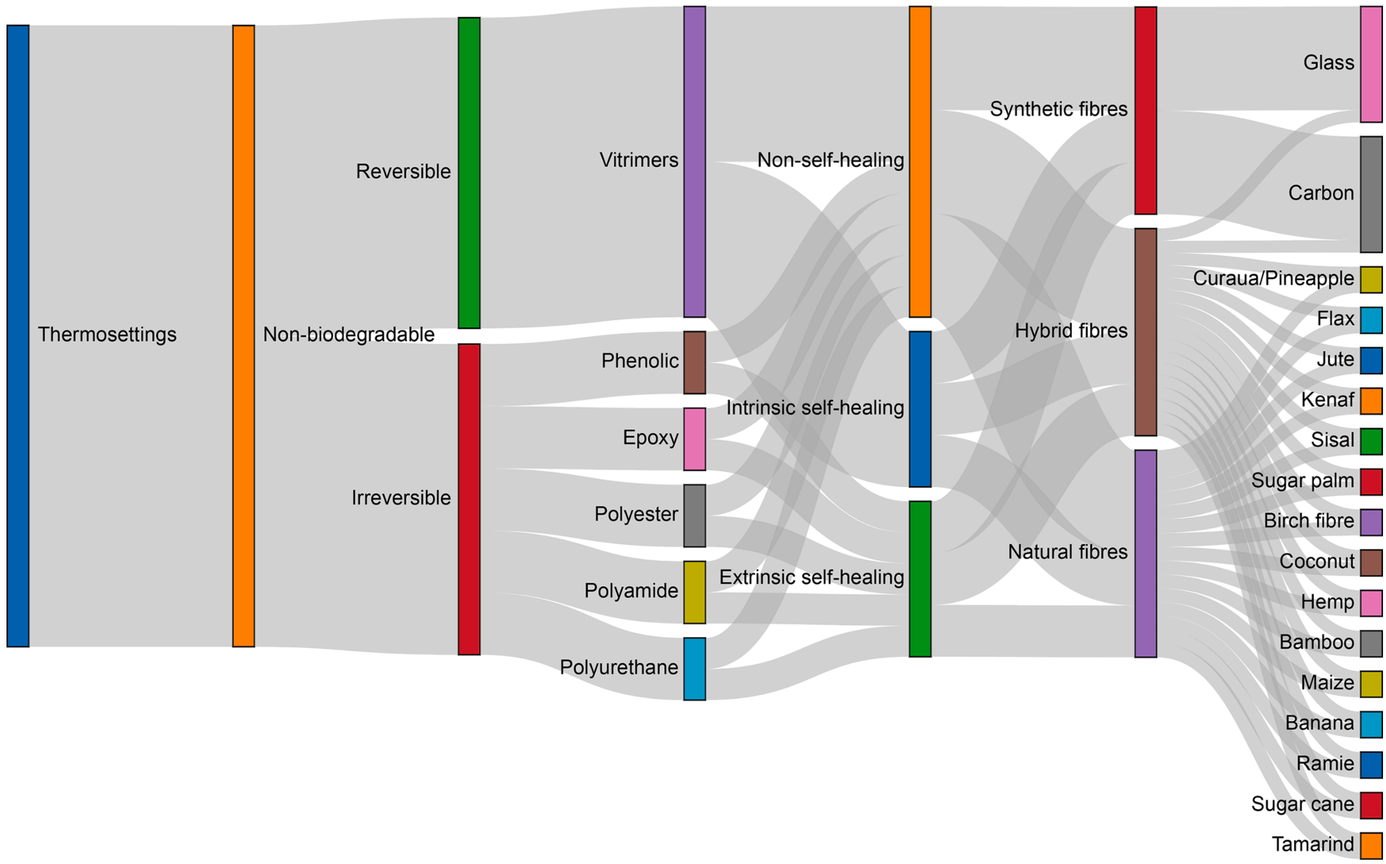

Fig. 6. Schematic of the different thermosetting resins that can potentially be used with combination with different fibre types to produce new polymer matrix composite materials for WTB.

4.1.3. *Reduce strategies*

With view on the end-of-life of future wind turbines. The use of sustainable materials and new manufacturing processes can help to cut from its roots the environmental impact of the next generation of WTB. This can be achieved with the introduction of Industry 4.0 technologies to simulate the behaviour of blades made of complex materials and the used of additive manufacturing processes to produce lighter, stronger, and more energy efficient blade geometries with less materials. The following sections present different potential material alternatives, new manufacturing technologies, and current industry efforts that can help to reduce the environment impact of WTB waste.

4.1.4. *Moving towards new materials and manufacturing methods*

The material requirements for WTBs are high stiffness to maintain optimal aerodynamic performance, low density to reduce gravity forces, and long-fatigue life (25 years with loading cycles of the order of 10^8–10^9) to reduce material degradation (Brøndsted et al., 2005; Swolfs, 2017; Mishnaevsky et al., 2017). These requirements limit the number of acceptable materials for large WTB. As a result, fibre-reinforced polymer composite (FRPC) materials are the preferred choice for the construction of large WTB due to their high strength, high stiffness, and low density, and their properties can easily be tailored (Sakellariou, 2018; Güemes et al., 2020; Kalkanis et al., 2019; Babu et al., 2006; Thomas and Ramachandra, 2018). Fibre-reinforced polymer composites (FRPC) are composed of a fibre-reinforcing phase embedded in a polymeric matrix (Jureczko et al., 2005). The reinforcing fibres serves to strengthening the composites. The function of the matrix is to adhere the fibres together for the efficient transfer of load between them (Gowda et al., 2018).

Most large WTB are made of glass fibre (GF) along with high-grade epoxy and polyester resins (Collier and Ashwill, 2011; Shrivastava, 2018). E-glass fibre ("E" because the initial electrical application) is the most common type of GF used in WTBs combining high strength, moderate stiffness, high electrical resistance and low cost (Mishnaevsky et al., 2017; Landesmann et al., 2015; Beauson et al., 2016; Batabyal et al., 2018). On the other hand, carbon fibre composites (CFCs) have superior mechanical properties than its counterparts made of GF (Elanchezhian et al., 2014; Huang, 2009), but they are significantly more expensive to fabricate (Naqvi et al., 2018). As a result, CFCs are used less frequently for WTB compared to GF composites (Jensen and Skelton, 2018). However, the wind turbine industry is slowly moving towards carbon fibre (CF) (Cranenburgh, 2019) and the hybrid combination of GF and CF composites (Collier and Ashwill, 2011) since the size of the blades is continuously increasing (Jensen and Skelton, 2018).

The polymer matrices are classified into thermoplastics and thermosetting, based on the type of bonding present in them (Gowda et al., 2018). The properties of the matrix determine the chemical resistance of the composite and its application. Resins such as epoxy, vinyl ester, and polyurethane dominate the composites market thanks to their ability to impregnate fibre, optimal chemical resistance, high thermal stability, low creep, and relaxation properties (Cousins et al., 2019; Caglio, 2019).

From a structural point of view, the main challenge in the design of WTB is to exceed the average lifespan of 25 years by overcoming the high-cycle fatigue (exceeding 100 million load cycles) of composites and material interfaces (bondlines, sandwich/composite interfaces) (Mishnaevsky et al., 2017). Production, quality control, and costs are other limitations of the scale-up applications of novel materials for WTB (Perry et al., 2012; Cherrington et al., 2012). According to Sakellariou (2018), original equipment manufacturers (OEMs) are mainly drawn to novel materials that are capable of reducing cost and manufacturing cycle times. As a result, little work exists in industry on alternative materials to counteract the environmental issues of current

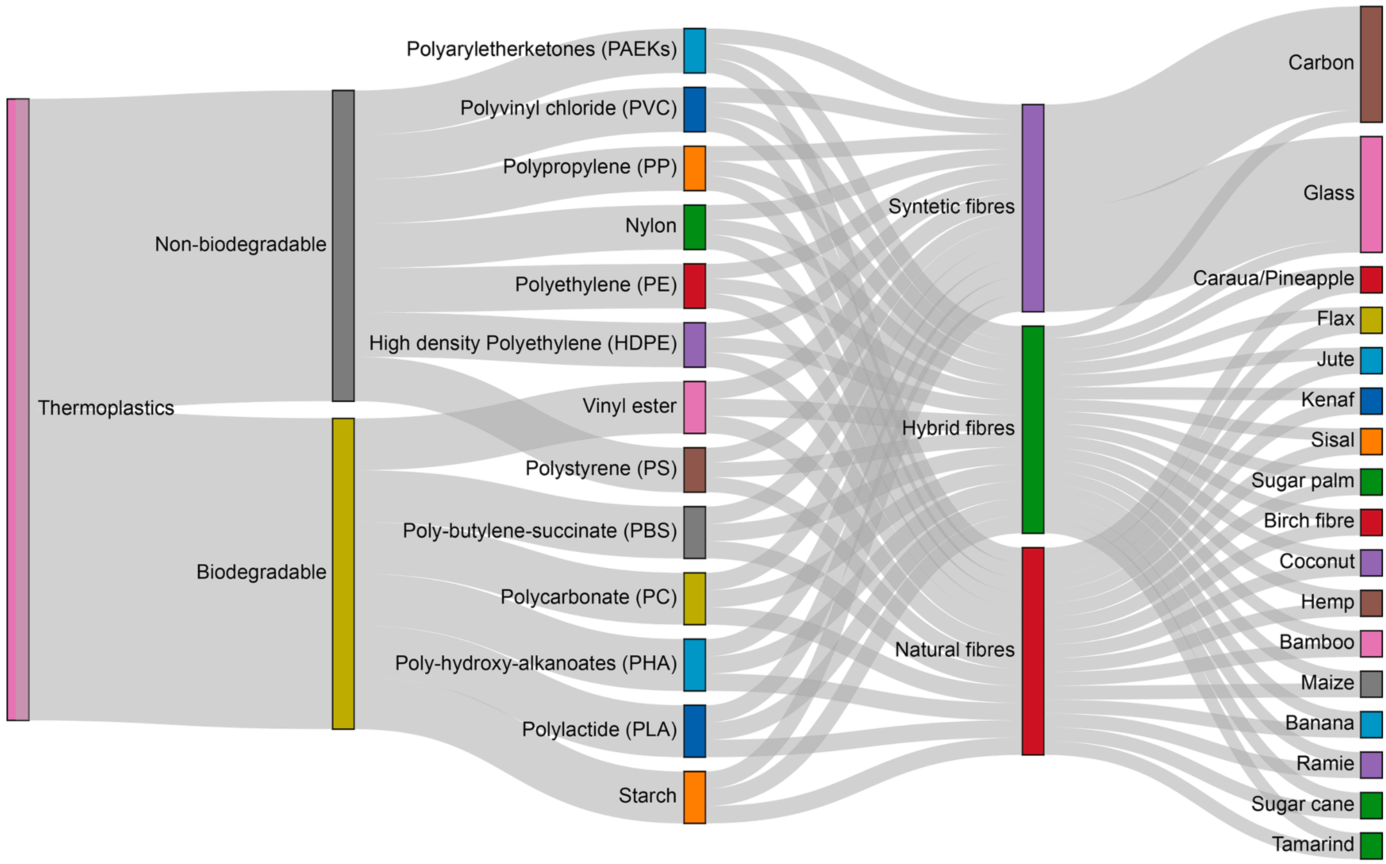

Fig. 7. Schematic of the different thermoplastic resins that can potentially be used with combination with different fibre types to produce new polymer matrix composite materials for WTB.

fibre-reinforced composites (Sakellariou, 2018). However, in the last two decades, numerous studies have been conducted and are under way to develop new materials for blades to improve performance and efficiency, reduce the volume of materials, and improve recyclability (Brøndsted et al., 2005). Some of these materials are reversible and self-healing thermoset resins, thermoplastic resins, biodegradable resins, natural fibres, and hybrid fibres composites. The different material alternatives for WTB are presented in Figs. 6 and 7 and discussed in turn below.

4.1.4.1. Reversible thermosetting resins. The current environmental issues caused by polymer matrix composites is due to the irreversible nature of thermosetting resins after they have been cured. Once they have been cured after the shaping processes, a permanent chemical change of cross-linking occurs in their molecular structure, which does not allow them to remelt through reheating (Cromwell et al., 2015). Thermosetting polymers cannot do the heating and cooling cycle repeatedly like thermoplastic polymers. As a result, many researchers have consequently developed thermosetting reversible systems that facilitate the reprocessability, reparability, and recyclability of these types of materials without reducing their mechanical properties (Wang et al., 2018). The first reversible thermosetting material, created by Leibler and his coworkers in 2011, was based epoxy resin with dynamic covalent bonds or covalent adaptable networks (CANs). Since then reversible epoxy thermosetting resins are considered a new type of polymer group called vitrimers (Wang et al., 2019).

At service temperature vitrimers have similar thermal and mechanical properties as traditional thermosets. However, when they are under the influence of an external force and above topology freezing transition temperature vitrimers can flow like a viscoelastic fluid (Yang et al., 2021). This property allows vitrimers to be reprocessed, reshaped, remoulded, and recycled at high temperatures (Yang et al., 2021). The main advantage of reversible thermosetting polymers is their potential to be incorporated into CE models. Other advantages are their low energy consumption and low equipment requirements for recycling (Lejeail and Fischer, 2021). Several strategies have been employed to produce different types of reversible thermosetting polymers by maintaining the inherent mechanical properties. These strategies use the amount of cleavable bonds in the cross-linked networks to depolymerise the material. Some of the strategies utilised for CF and GF composites are based on ester bonds, acetal linkages, a Schiff base structure, disulphide bonds, a hexahydrotriazine structure, boronic ester bonds (Wang et al.,

Table 3
Mechanical properties of some CFRPs based on degradable thermosets with different reversible linkages for potential use in WTB and two conventional high-performance aeronautical CFRPs (T300/914 and T300/5405), adapted from (Wang et al., 2019; Yuan et al., 2017).

CFRP material	Tensile strength (MPa)	Young modulus (GPa)	Elongationat break (%)	Flexural strength (MPa)	Flexural modulus (GPa)
T300/914	631	70	–	912	61
T300/5405	1787	147.8	–	1560	108
Acetal epoxy/plain weave CF	1343–1375	66.8–73.9	1.75–1.82	–	–
PHT/unidirectional CF	1806.6	141.7	1.4	1241.2	127.4
PHT/cross-plyCF	741.2	68.3	1.2	829.7	54.8

2018), and di-N-benzylaniline linkage (Wang et al., 2019). For example, Yuan et al. (2017) designed a new synthesis scheme for degradable thermosetting resins with stable covalent structures and prepare a recyclable CF-reinforced poly(hexahydrotriazine) resin matrix advanced composite. Their results demonstrated that reversible CFRP materials can achieve similar or better mechanical properties than high-performance aeronautical CFRP, as shown in Table 3 (Yuan et al., 2017). Furthermore, the reversible thermosetting resins can be recycled multiple times barely affecting the architecture, length and performance of the CF (Yuan et al., 2017). The challenges of these materials are their water sensitivity (Liu et al., 2019) and little attention that has been paid to their actual usage on an industrial scale (Post et al., 2019). Nonetheless, several degradable thermosets CFRPs have been developed with promising mechanical properties for WTB applications, as shown in Table 3.

4.1.4.2. Self-healing thermosetting resins. Another strategy to prevent the environmental impact of thermosetting polymers is to extend their lifespan with self-healing properties. In the case of wind turbines, self-healing thermosetting materials can help to reduce the service costs and extend the turbines' lifespan by reducing the notch stress in the material (Paolillo et al., 2021). In the last decade, numerous strategies have been used to create self-healing thermosetting materials, and according to Zhang (Zhang, 2020), these approaches can be categorised into two main groups: intrinsic and extrinsic strategies. On the one hand, intrinsic self-healing materials possess latent self-healing functionalities that are triggered by damage or by external stimulus such as heat, light, and solvents, among others (Paolillo et al., 2021). The main advantages of these materials are their multiple healing cycles (Urdl et al., 2017). However, in the case of WTB, this strategy is not optimal due to the high costs and difficulties of manual maintenance, especially in remote areas. Moreover, because of their high viscosity, these materials' self-healing property is limited to small damage volumes (Kim and Yoshie, 2018).

On the other hand, extrinsic self-healing materials are appropriate for WTB applications due to their autonomous recovery. Extrinsic methods compromise the use of embedded microcontainers such as microcapsules, microvascular networks, or nanoparticles that are used to heal the crack site upon fracture. These microcontainers are designed to rapidly release a healing agent to fill the damaged area and restore its mechanical integrity (Mphahlele et al., 2017). The advantages of using extrinsic self-healing materials are their reliability, flexibility, and ability to heal large cracks (Urdl et al., 2017). For wind turbine blade applications, several self-healing materials with vascular networks have been studied (Arun Kumar Koralagundi et al., 2017; Arun Kumar Koralagundi et al., 2015; Shen et al., 2019). For example, Shen et al. (2019) developed a self-healing material for WTB with a unilateral vascular network containing dicyclopentadiene as the healing agent and Grubbs' first-generation catalyst. According to Shen et al. (2019), the vascular network had the ability to repair small and large fractures and multiple damage events with an average recovery of flexural strength of 80%. In a more recent study, Shen et al. (Shen et al., 2020) used a pressurised pump to deliver a healing agent through borosilicate vascular vessels in a blade made of GF composite. According to their results, after a 25-J impact, the material's flexural strength was able to recover up to 55% after healing. In general, the drawbacks of extrinsic methods are the low number of healing cycles in the same volume; an inadequate mixing of healing agent; and expensive production, including the challenge of not altering the physical and mechanical properties of the polymer matrix with the embedded microcontainers (Zako and Takano, 1999; Lv and Chen, 2013).

Overall, self-healing polymer composites are promising materials with the potential to reduce maintenance costs and increase the lifespan and reliability of WTB. However, self-healing thermosetting composite materials for high-performance applications must first overcome key challenges, such as their healing efficiency at ambient temperatures, and provide high mechanical properties to the healed volume (Kim and Yoshie, 2018; Khan et al., 2020). In Fig. 6 are represented the configurations of different thermosettings resins with the different types of available fibres.

4.1.4.3. Thermoplastic resins. There is an increasing trend towards using thermoplastic resins in long and short fibre composites outside of the wind industry (Greene et al., 2022; Bruijn and van Hattum, 2020) and a growing interest in utilising these resins for blade fabrication (Murray et al., 2021; Manap et al., 2020). Thermoplastic resins, which are inherently recyclable, are potentially a better design choice due to the tightening regulations on composite waste landfilling. Thermoplastic resins for composite applications have several advantages over thermosetting resins and can potentially introduce cost savings.

Thermoplastic materials can be thermally welded, thus eliminating the need for adhesive bonds between blade skins and increasing the overall strength and reliability of the blades, and they can be reformed by applying high temperatures, thereby enabling easier repair and maintenance. The latter ability presents a potential advantage over currently used thermosetting resins such as epoxy, which cannot be reformed other than by machining and by putting the material properties at risk of damage (Murray et al., 2017). Moreover, thermoplastic materials provide shorter manufacturing cycle times, and in-situ manufacturing of the wind blades is possible, thus removing the transportation limitations to accommodate larger blades (Cousins et al., 2019; Murray et al., 2017). In terms of mechanical performance, the most promising thermoplastic resin for WTB is Elium®, developed by Arkema Inc. This resin has demonstrated mechanical properties and capabilities comparable to epoxy resins (Bhudolia et al., 2020).

From a cost perspective, Murray et al. (2019) have shown that wind turbine composite blades made of thermoplastic can cost 4.7% less than an equivalent epoxy blade. According to Murray et al. (Murray et al., 2019), the reduction in the cost of thermoplastic blades is due to factors, such as a reduction in capital costs, quicker cycle times, and less labour and energy requirements. Nonetheless, despite the advantages of thermoplastic resins for fibre-reinforced composites, their use in large WTB has not yet been exploited by the energy industry. Therefore, for thermoplastic fibre-reinforced composite blade technology to become commercially viable, efficient and reliable manufacturing with adequate quality standards must be established (Murray et al., 2021).

4.1.4.4. Biodegradable resins. Due to their low cost and their long-lasting, high-performance properties, petroleum-derived plastics have become indispensable to daily life and the global economy. However, the disposal of non-biodegradable polymers has resulted in a severe environmental disaster (Mrowiec, 2018). As a result, biodegradable polymers have recently received substantial attention, especially for their potential to create a new generation of biodegradable fibre-reinforced composites (Ramesh et al., 2017).

Biodegradable polymers originate from four different sources, namely, petrochemical synthesis (e.g. polycaprolactone [PCL], polyvinyl alcohol [PVA]), microbial synthesis (e.g. polyhydroxyalkanoates [PHA], Polyhydroxybutyrate [PHB]), renewable resources (e.g. polylactic acid [PLA], starch), and animal sources (e.g. casein, gelatine, collagen) (Tholibon et al., 2019). Thanks to their low melting points (under 200 °C), the most representative biopolymers for composite applications are PLA, PHA, and polybutylene succinate (PBS). First, PLA is one of the most promising biopolymers to substitute for petroleum-based polymers, making it the focus of numerous investigations (Sanivada et al., 2020). Composites made of PLA present optimal mechanical properties for engineering applications. For example, composite materials made of PLA and flax fibre have been reported to have similar mechanical properties compare to GF or polypropylene (PP), which is widely used in industrial applications (Pantaloni et al., 2020). Moreover, they can be manufactured with some

Table 4
Mechanical properties of natural and synthetic fibres.

	Tensile strength (MPa)	Young modulus (GPa)	Elongationat break (%)	Density (g cm^{-3})	Specific stiffness (GPa cm^3 g^{-1})	Specific strength (MPa cm^3 g^{-1})	Ref.
Natural fibres							
Hemp	270–900	24–90	1.0–3.5	1.20	20–75	225–750	(Fitzgerald et al., 2021)
Banana	500	12	4.5–6.5	1.00–1.50	8–12	330–500	(Fitzgerald et al., 2021)
Kenaf	223–930	15–53	9.1–12.3	1.20–1.40	11–44	160–775	(Fitzgerald et al., 2021)
Flax	370–1480	40–105	1.2–3.3	1.38–1.54	26–76	240–1070	(Fitzgerald et al., 2021)
Jute	610–780	12–60	1.0–1.9	1.30–1.50	8–46	410–600	(Fitzgerald et al., 2021)
Ramie	180–1630	1–83	1.6–14.5	1.00–1.55	0.6–83	115–1630	(Fitzgerald et al., 2021)
Curaua	540–1400	12–50	3.0–4.3	1.40–1.50	8.4–36	360–1000	(Fitzgerald et al., 2021)
Sisal	540–720	10–40	2.2–3.3	1.30–1.60	6.3–31	340–550	(Fitzgerald et al., 2021)
Bamboo	445–752	27–40	1.9–3.2	1.20–1.50	18–33.3	370–627	(Khalil et al., 2012; Perremans et al., 2018; Wang et al., 2015)
Pineapple	126–1627	4.2–82.5	1.6–4.0	1.07–1.52	2.76–77	117–1520	(Asim et al., 2015)
Tamarind	61–156	2.18	6.22	1.04–1.60	1.3–2	58.6–150	(Nayak et al., 2019; Uma Maheswari et al., 2008)
Coconut	100–500	3.7–6	20	0.14–1.37	2.7–42.8	73–3571	(Ali, 2011)
Sugar cane	169	5.8	6.25	–	–	–	(Hossain et al., 2014)
Sugar palm	190.29–292	3.37–3.69	19.6–24	1.29	2.6–2.8	147.51–226	(Bachtiar et al., 2009; Ishak et al., 2012)
Silkworm Silk	175–1400	1–16	4–34	1.34	0.8–12	130–1050	(Fitzgerald et al., 2021)
Spider Silk	750–1840	2–21	17–52	1.32–1.35	1.5–16	550–1400	(Fitzgerald et al., 2021)
Synthetic fibres							
Glass	1700–4900	72–89	4.7	2.54–2.57	28–35	661–1929	(Krauklis et al., 2021)
Carbon	1800–6000	230–724	1.5–2.0	1.78–1.95	118–406	900–4000	(Krauklis et al., 2021)

newly developed manufacturing technologies such as AM (Guduru and Srinivasu, 2020; Pop et al., 2020).

Second, PHA is a group of polyester polymers produced by bacteria (Loureiro et al., 2014). This group of polymers has mechanical properties comparable to some thermoplastic polymers used in fibre-reinforced composites (Tang et al., 2020). The disadvantages of PHAs are their slow biosynthesis and high cost (Tang et al., 2020). Third, PBS is a biodegradable synthetic polyester of petrochemical origin (Encisoet al., 2020). PBS stands out for its high melting point, optimal processability, and excellent mechanical properties (Encisoet al., 2020).

Unfortunately, all biodegradable polymers have 'performance and processing' issues. For WTB, some of these issues include low mechanical properties and fibre affinity (Pantaloni et al., 2020a, 2020b). Several research efforts are hence under way to create blends of these polymers, such as PHA/PLA and PLA/PBS, to enhance their mechanical properties and achieve controlled biodegradability (Pantaloni et al., 2020; Larguech et al., 2020). In Fig. 7 are represented the configurations of different thermoplastic resins with the diffent types of available fibres.

4.1.4.5. Natural fibres. Natural fibres are renewable material resources. They are abundantly available from renewable sources – both plants and animals (Bravo et al., 2018). The most common organic fibre is cellulose, and the most common natural composite is timber. Plant fibres such as flax, hemp, and jute are cheap and have both better stiffness per unit weight compared to GFs and good tensile modulus and flexural modulus (Caglio, 2019). They can thus be utilised for many load-bearing applications. In general, the strength of a plant fibre increases with increasing cellulose content and decreasing spiral angle with respect to the fibre axis (Caglio, 2019). Natural fibre-reinforced composites have several advantages compared to synthetic fibres, for example lower density and higher specific strength and stiffness, as shown in Table 4. Moreover, the modulus of elasticity of some natural fibres is comparable to that of GFs, making them attractive candidates for the development of green composites (Jagadeesh et al., 2017). Other advantages are that the process of manufacturing natural fibres does not create any health-related issues for workers, and their extraction process is simple and can be done with unskilled labour. Finally, the cost of natural fibres is low, and they possess higher biodegradability (Yahaya et al., 2014; Mohammad and Mohamed, 2018).

Nonetheless, the greatest challenge in working with plant fibre-reinforced composites is their large variation in natural properties and characteristics, which depend on the harvesting region, harvesting time, soil condition, intensity of sunrays, and rain. The hydrophilic and hydrophobic properties of natural fibres and polymers, respectively, cause poor bonding interaction at their interface (Lau et al., 2018). Furthermore, natural fibres have low microbial resistance, which creates problems during shipment, long-term storage, and composite preparation. Finally, natural fibres have limited thermal stability: the permitted temperature is up to 200 °C; beyond this temperature, the fibre will degrade and shrink (Lau et al., 2018). When natural fibres are subjected to heat, the physical, chemical, and structural behaviour of the composite generally changes, leading to dehydration, oxidation, recrystallisation, hydrolysis, and decarboxylation (Ramesh et al., 2017; Yahaya et al., 2014; Mohammad and Mohamed, 2018). Therefore, to meet the specific mechanical and other properties, similarly to synthetic fibre composites, most of natural fibres are chemically modified with different surface treatments to increase the compatibility between the fibre and matrix (Jagadeesh et al., 2017; Mohammad and Mohamed, 2018).

Additionally, from the engineering design point of view, the mathematical and numerical models used to predict the mechanical properties of natural-fibre-reinforced composites are limited. Some of the reasons are the complicated microscopic structures of natural fibres, the varying diameter of the fibres along their length, and the difficulty of having accurate input data. Moreover, the microfibrils of natural fibres are not identical, as they are composed of crystalline and amorphous regions (Lau et al., 2018). Modelling natural fibres is more challenging and traditional modelling methods cannot be applied (Lau et al., 2018).

4.1.4.6. Natural hybrid, natural/synthetic and carbon/glass composites. Vast improvements in both mechanical and water absorption properties have been reported with fully natural hybridised composites (Gowda et al., 2018). These composite materials are composed of two different types of natural fibres with a polymeric matrix. According to Jawaid et al. (2011), some natural hybrid composites can provide similar strength as synthetic composites. However, according to design and manufacturing experts, a complete replacement of existing synthetic fibre with natural fibre is not possible for high-performance applications (Mishra et al., 2020), such as wind turbine applications. As a result, hardly any work is being done to develop such materials as an

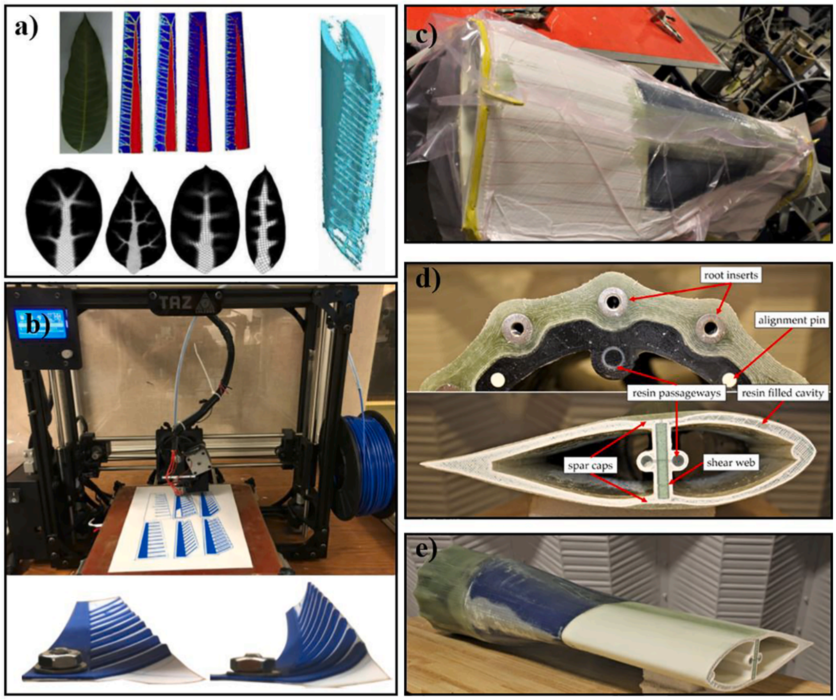

Fig. 8. a) Topology optimization simulation of plant-leaf WTB structure (Liu, 2011); b) 3D of printing plant-leaf mimetic architecture prototypes (top), originally printed flat blade without heat treatment (left), and bend-twist coupling after heat treatment (right) (Momeni et al., 2019); c), d), and e) Conceptual tidal turbine blade section during infusion process and final finished blade (Murdy et al., 2021).

alternative for the fabrication of wind blades (Sakellariou, 2018) .

A less common type of composite material are hybrid of natural and synthetic fibres (Jawaid and Khalil, 2011). Hybrid composites reinforced with natural fibres, often combined with synthetic fibres such as GFs, demonstrate good mechanical performance, as well as weight and cost savings (Jawaid and Khalil, 2011; Sapiai et al., 2020; Belfkira et al., 2020). In addition, the partial replacement of synthetic fibre with natural fibre can reduce the harmfulness to environment and increase the biodegradability of existing synthetic fibre composites (Mohammad and Mohamed, 2018).

The drive for increased blade length is pushing turbine manufacturers to shift from GF composite blades towards CF/GF-hybrid composite blades. The advantages of using CF/GF-hybrid composites is the balance in blade weight and performance that could be achieved through proper material design (Jawaid and Khalil, 2011). By adding CF in the regions where load bearing is needed the most, and GF in all other regions, it is able to further increase the blade length without increasing too much weight (Swolfs, 2017; Jawaid and Khalil, 2011).

4.1.4.7. Nanofillers for fibre reinforced composites. An approach to enhance the properties of polymer matrix composites is the use of nanomaterials as fillers. Nanofillers are used to increase the number of particle-matrix interactions at the molecular level thanks to their large surface area to volume ratio (Njuguna et al., 2008). According to the ISO/TS 80,004–2:2015 standard (ISO 2015), nanofiller materials can be classified as one-dimensional, two-dimensional, or three-dimensional and further classified according to their composition as either organic or inorganic – a large variety of nanofillers can be organic or inorganic. The most studied nanofillers for polymer matrix composites are cellulose nanocrystals (Ferreira et al., 2018), nanodiamonds (Wang et al., 2020), nanoclays (Bhattacharya, 2016), carbon black, fullerene (Li et al., 2019), carbon nanotubes, graphene (Kozlov et al., 2019), nano-oxides, and metallic nanoparticles (Hasan et al., 2014).

Nanofillers largely extend the functionality of polymer matrix composites by improving their electrical, optical, and mechanical properties, as well as providing better resistance to water and fire (Marquis et al., 2011). Nanofillers can also reduce the cost of composite materials and facilitate their fabrication process (Khanam et al., 2015). For aerospace and military applications, inorganic nanofillers have been used with fibres such as glass, carbon, or aramide fibres to improve the impact resistance, tensile strength, and modulus of elasticity of composite materials (Marquis et al., 2011; Kausar et al., 2017; Matadi Boumbimba et al., 2017). In the case of WTB, nanofillers can be employed to enhance the blades' lifespan by increasing the material stiffness and fatigue limit (Mechin et al., 2020). To meet the current environmental concerns, nanofillers have been utilised to improve the mechanical properties of biodegradable resins (Sun et al., 2018) and improve the compatibility of natural fibres with a polymer matrix (Devnani and Sinha, 2019; Begum et al., 2020; Joseph et al., 2020). Moreover, nanofillers can also be used to create polymer matrix composites with self-healing properties (Vijay Kumar et al., 2019).

Despite the several advantages provided by the use of nanofillers for polymer matrix composites, there are two important considerations. First, nanofillers must be carefully selected, taking into consideration their compatibility with the resin and the fibres used. Second, achieving a homogeneous dispersion during the mixing process with the polymer resin is vital. This will provide a strong interaction between the nanoparticles and the polymeric matrix (Oksman et al., 2016), otherwise particle agglomerates and void formation may appear during the fabrication process, which will lead to a detriment of material performance due to low fibre impregnation and adhesion (Mechin et al., 2020; Šupová et al., 2011).

4.1.5. Additive manufacturing

The main fabrication methods of WTB are vacuum-assisted resin transfer moulding (VARTM) and Seeman's composite resin infusion process (SCRIMP) (Tholibon et al., 2019; Veers et al., 2003; Veazey et al., 2017). VARTM is the simplest resin infusion method and dates back to the 1950s (van Oosterom et al., 2019). The SCRIMP method, is a modified version of VARTM designed to improve the fabrication efficiency of large parts (van Oosterom et al., 2019). Advances in blade-manufacturing automation have reduced manufacturing times from 38 h to 24 h per blade (Murray et al., 2017). However, despite improvements in resin infusion WTB fabrication is a complex, energy-intensive, and expensive process that strongly rely on human labour (Schubel, 2010; Ong et al., 1999; Camanho and Matthews, 1997; Post et al., 2017; Smith, 2000). Therefore, there is a need to explore new, more affordable manufacturing capabilities, potential solutions, and strategies for WTB (Murray et al., 2017).

Promising manufacturing technologies such as additive manufacturing (AM) can potentially change and offer the opportunity to overcome some of the challenges of WTB fabrication methods, such as cost, labour intensiveness, and time consumption. Additive manufacturing fabricates parts by joining the material layer by layer (ISO/ASTM 2015).

The main advantage of AM technologies is their ability to fabricate complex shapes that are not possible with traditional manufacturing methods. Therefore, the need to design for manufacturing becomes obsolete, thus eliminating traditional design constraints (Ferreira et al., 2017; Tofail et al., 2018; Hollister et al., 2018). Furthermore, due to the manufacturing flexibility of AM, just-in-time production becomes the natural manufacturing environment, where short lead times to market are required (Esmaeilian et al., 2016; Zhong et al., 2017; Dennis, 2007). Another advantage is that product costs are drastically reduced because the production chain is reduced to a small number of processes, requiring less machinery and space. Moreover, AM has a low environmental impact because the material used during fabrication is minimal, and the unused material can be recycled, thereby producing less waste (Reeves, 2008).

With the use of AM, it is also possible to create blade designs that challenge the traditional blade design of WTB. For example, Momeni et al. (2019) used a biomimicry approach to design a different kind of WTB based on plant leaves. Several studies had previously demonstrated that blades designed based on the branched network of leaves have smaller stress intensity, better static strength and stiffness, lower internal strain energy, and higher fatigue (Liu, 2011; Liu and Zhang, 2010; Wangyu et al., 2022). Starting with this biomimetic concept, Momeni et al. (2019) fabricated a wind turbine prototype with reversible bend-twist coupling behaviour that is in favour of aeroelasticity (Fig. 8a and b). Moreover, the blades were designed to change the shape without the need for electromechanical actuators and moving parts. This was attained by using a 4D printing process with a shape memory polymer. Even though Momeni et al. (2019) only presented a small-scale prototype, it demonstrates that in the future, with advances in AM, fabricating better large turbine blades with a biomimicry design approach may be possible.

In another study, Murdy et al., (2021) explored the use of AM to fabricate moulds to produce hybrid composite tidal turbine blades for marine energy systems. However, their approach to fabricate the blade was to use an internal permanent mould instead of two non-permanent moulds as is traditionally done for resin infusion processes (Fig. 8c,d, and e) (Murdy et al., 2021). According to Murdy et al. (2021), the advantage of using a permanent mould is that allows the application of continuous fibres around the mould to create a single-piece blade with lower fatigue concentration areas and manufacturing defects. Moreover, this fabrication approach is more cost effective because it cuts several manufacturing steps (Murdy et al., 2021). Nevertheless, the disadvantage of the authors' blade fabrication method is that every blade will require the fabrication of its respective internal mould, whereas by using the traditional approach, a single mould can be used to produce hundreds of turbine blades (Murdy et al., 2021). Moreover, the application of Murdy et al.'s fabrication approach for large turbine blades will require the fabrication of the blades in different sections, which will then need to be assembled to create a single blade.

Modular WTB can help to overcome the challenges of fabricating and transporting large WTB (Peeters et al., 2017; Garate et al., 2018). Moreover, modular WTB can be fabricated with thermoplastics using AM, and the process can be scaled for large blades. Based on this concept, several researchers have proposed the use of AM for on-site production of WTB. For example, Khakpour Nejadkhaki and Hall (2018) proposed the design concept of an adaptive WTB with a bend-twist coupling design. According to Khakpour Nejadkhaki and

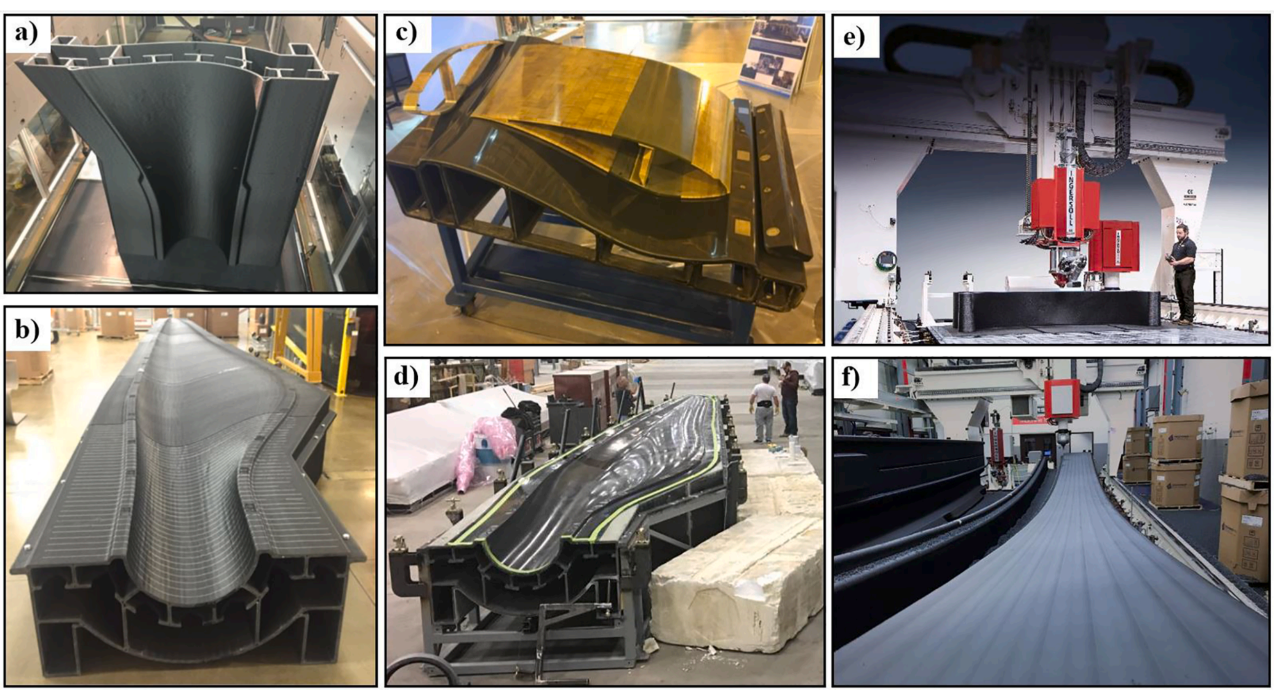

Fig. 9. 3D printed wind turbine mould by Oak Ridge National Laboratory a) Low pressure section; b) Five out of eight low pressure side mould sections; c) Additively manufactured blade mould and produced blade section; d) Final high pressure mould, images a, b, c, d, and e by kind permission of Brian K. Post from (Post et al., 2017); e) Size comparison of the MasterPrint WHAM system the largest 3 printer in world; f) demonstration of the MasterPrint 3D printer capabilities, by kind permission of Ingersoll and Camozzi (Camozzi 2021).

Hall (2018), a bend-twist coupled WTB can provide better energetic performance and reduce fatigue damage. For wind turbine blades to achieve various shapes, they must be modular and ideally be fabricated using AM to facilitate their production, transportation, and installation (Khakpour Nejadkhaki and Hall, 2018). In a different study, Bassett et al. (2015) identified the considerations for the design and additive manufacture of a small wind turbine. Even though this study only focused on vertical axis wind turbines, it concluded that with current accessible AM systems, the blades must be fabricated to be ensembled in a modular way. Overall, Bassett et al. (2015) proposed that additively manufactured wind turbines can be easily applied for rural electrification, disaster relief, and humanitarian projects.

4.1.6. *Current reducing industry initiatives*

Thanks to technological advances on novel polymeric materials and manufacturing methods there are several successful and running industry initiatives that are focused in pioneering new ways to reduce the environment impact of WTB. For example, Siemens Ganesa recently launched in Aalborg, Denmark the world's first recyclable blade made of glass fibre and a reversible thermosetting resin (Siemens-Gamesa 2021). The 81-m Recyclable Blades from Siemens Ganesa will be first installed at the Kaskasi offshore wind power plant in Germany (Siemens-Gamesa 2021). According to Siemens Ganesa, goal is to make turbines fully recyclable by 2040 (Siemens-Gamesa 2021).

Another example is ÉireComposites, an Irish company with a unique blade-manufacturing system to produce blades made of thermoplastic resin (polypropylene) and glass fibre for 6-kW and 15-kW wind turbines (EireComposites 2021). According to ÉireComposites (EireComposites 2021), its thermoplastic blades are 25% cheaper and require a 33% lower production cycle than its thermoset equivalents. Similarly, a French company called Arkema has developed a reactive monomeric thermoplastic resin called Elium, which can be polymerised into a solid form after infusion (Murray et al., 2021). Arkema, in collaboration with the National Renewable Energy Laboratory in the US, has demonstrated the potential of Elium resin for WTB. For this purpose, a 13-m-long WTB was fabricated and structurally compared with a near-identical epoxy composite blade (Murray et al., 2021). According to the company's results, the thermoplastic blade exhibited a structural performance similar to its epoxy counterpart. However, the thermoplastic blade presented five to seven times more structural damping, which may result in reduced operational loads (Murray et al., 2021).

There have been several industry research collaborations to explore different ways to use AM for the fabrication of WTB. For example, LM Wind Power, a Danish company that is part of GE's renewable energy business, recently entered into a two-year project to fabricate high-performance WTB with AM (Power, 2021). The project is anticipated to cost $6.7 million, and it will be delivered in partnership with the Oakridge National Lab and the National Renewable Energy Lab. According to LM Wind Power, the focus of the project is on demonstrating the fabrication of full-size blades made of low-cost thermoplastic skin coupled with 3D printed reinforcement (Power, 2021). This will allow for the fabrication of lighter blades made of more recyclable materials, which in turn will lower manufacturing costs and increase supply chain flexibility (Power, 2021).

Another example is Oak Ridge National Laboratory (ORNL) in the US who demonstrated that is possible to additively manufacture high-performance moulds for WTB (Post et al., 2017). For this purpose, ORNL used a Big Area Additive Manufacturing (BAAM) system to manufacture 16 different mould sections for a 13-m-long wind turbine (Fig. 9a – d). The moulds were manufactured with integrated heating channels for uniform heating of the mould surface. According to Post et al. (2017), the mould design eliminates the manual labour associated with the assembly of the heating system. Moreover, the higher productivity and lower material cost and energy intensity of AM provides a significant production cost reduction compared to conventional manufacturing systems (Post et al., 2017). In another project performed by ORNL, AM was utilised to identify the benefits and applicability of the development and prototyping of wind turbines. For this purpose, prototype blades were additively manufactured with a BAAM system using 20% CF-reinforced acrylonitrile butadiene styrene polymer. According to Post et al., (2020), they were able reduce development and prototyping time from twenty-four to six weeks. Moreover, the tested prototypes were able to resist a load-carrying capacity 3.4 times the nominal load capacity (Post et al., 2020).

To overcome some of the limitations of blade manufacturing based on moulds Ingresoll Machine Tool company in partnership with ORNL developed the first Wide High Additive Manufacturing (WHAM) system with built-in computer numerical controlled milling capabilities. The MasterPrint WHAM system can 3D print objects withing a working volume of 6 m x 4 m x 2 m and it can be equipped with a 3 or 5 axis milling head (Fig. 9e and f) (Camozzi 2021). This competitive 3D system can be used to manufacture complex design blades and moulds made of thermoplastic carbon fibre composite materials producing less material waste.

4.2. *Refurbish and remanufacture*

Refurbishment or remanufacturing is the process of restoring products and components with the intention re-establish their functionality to "as new" quality. The difference refurbished and remanufactured is that remanufacturing involves restoring by to the original manufacturer specifications (Environment, 2016). This makes remanufactured wind turbines more reliable and expensive than their equivalent refurbished. Despite the mentioned differences refurbished and remanufactured wind turbines provide several advantages in terms of costs and environment impact. For example, they can be bought for as little as half the cost with a warranty for life extensions varying from 2 to 5 years for refurbished and 5–20 years for remanufactured (Ortegon et al., 2013). This also allows to increase their service life and value of an end-of-life wind turbine to contribute to the circular economy cycle of WTB.

One of the industry contributors to the refurbishing of wind turbines is the Dutch company Dutchwind BV. This company services include the decommission, sales, transport, and erection of refurbished wind turbines (Duchwind 2021). During the refurbishment/remanufacture of WTB the main objective is to restore the strength and stiffness of the composite material to bring back its structural and operational efficiency to then repaint and balance the blades (Armstrong et al., 2005). To identify the condition of decommissioned WTB there are several standardized procedures such as visual inspection, ultrasonic inspection, and natural frequency measurements (Ostachowicz et al., 2016). Then after identifying the blade structural condition repairs different types of repairs are performed using bonded doublers or scarf patches (Katnam et al., 2015). Damaged sandwich shells often require replacing the damaged core and bonding a replacement core and skin sheet (Katnam et al., 2015). However, refurbishment/remanufacture of large wind blades can be a challenging task in terms of logistics and accessibility, as well how they get disassembled, reprocessed, and reassembled can greatly affect the quality of a refurbished blade (Ramesh et al., 2017). Moreover, compared to aerospace structural repair procedures in wind blades are not as well developed (Katnam et al., 2015). Therefore, it is important that new WTB designs should facilitate blade disassembly and refurbishment (Ortegon et al., 2013).

4.2.1. *Repurpose strategies*

Repurposing is another way in which to avoid the landfilling of WTB. Blade repurposing is the practice of using an existing part of the blade for a different application, usually of lower value than the original. The repurposing of composite blades is generally considered to be safe; however, different processes and treatments are required to protect the repurposed blades from the environment and as a precaution to avoid exposing users to sharp GFs (Medici et al., 2020). Wind turbine blades can be repurposed in different ways: they can be used to create power

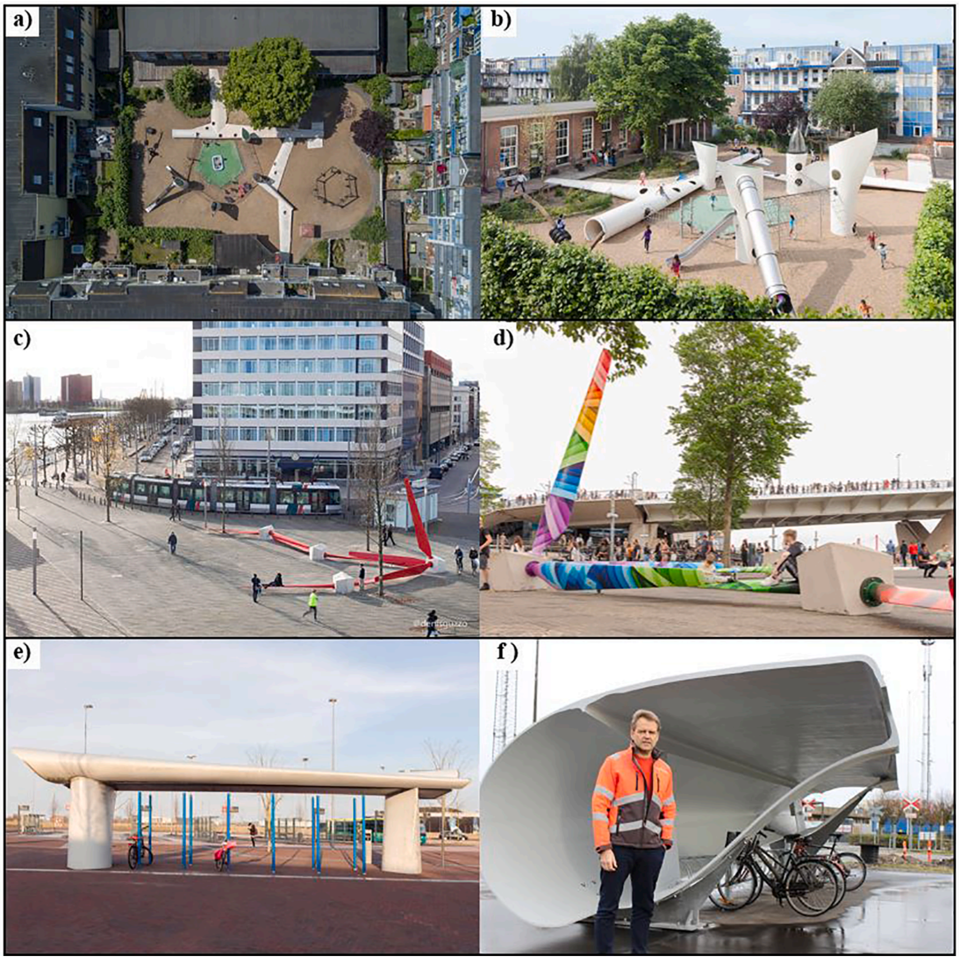

Fig. 10. Examples of architectural use of WTBs: a-b) The Wikado playground designed by uperuse; c-d) Public seating in Willemsplein, Rotterdam before and after repainting; e) Bus stop shelters at Almere Poort's station designed by Superuse, by kind permission of Denis Guzzo (Guzzo, 2019); f) Bike shed in Port of Aalborg Denmark, by kind permission of Henrik Eilers (Eilers, 2020).

transition poles (Alshannaq et al., 2019), playgrounds, shelters and housing (Bank et al., 2018), bridges (Jensen and Skelton, 2018), walkways, street furniture, and architectural pieces (Schmid et al., 2020). Nonetheless, the current limitations of repurposing are the lack of standards as well as design and certification guidelines, the difficulty to implement it at a large scale, and social acceptance in relation to the intended reuse application (Joustra et al., 2021).

4.2.2. *Repurposing industry initiatives*

Several industry initiatives and research projects are currently under way to demonstrate the different ways in which WTB can be repurposed. For example, Superuse Studios is a Dutch architectural firm responsible for several projects where WTB were used to produce architectonic solutions with a circular and sustainable design approach. One of the firm's projects, five blades were used to create an entire playground of 1200 m^2 called Playground Wikado (Studio, 2021), as shown in Fig. 10a and b. According to Superuse, by the repurposing WTB in this project, it was able save approximately 90% CO_2 emissions compared to a normal playground (Studio, 2021). In another project, called 'REwind Willemsplein', nine blades were transformed into ergonomic urban furniture to be used at the foot of the Erasmus Bridge in Rotterdam (Fig. 10c and d) (Studios, 2021; Guzzo, 2019).

Two additional examples of WTB repurposing are the bus stop at Almere Poort's station and by the *Re*-Wind project (Guzzo, 2019) and the bicycle shelter built at Aalborg harbor in Denmark (Eilers, 2020), as presented in Fig. 10e andf respectively. The latter project involves researchers in the Republic of Ireland, Northern Ireland, and the US and was founded by all three governments (*Re*-Wind 2021). The aim of the *Re*-Wind project is to explore and deploy innovative design and logistical concepts for reusing blades across architecture and engineering (*Re*-Wind 2021). Some of its different innovative ideas are the use of blades as wave attenuators on coastlines for erosion prevention, mobile phone towers, roof trusses, skate parks, and artificial reef scaffolds, as well as in geo retention and housing, amongst other things (*Re*-Wind 2018). In 2021, the *Re*-Wind project will have two large-scale demonstrations, namely, a pedestrian bridge and a blade pole, in County Cork, Ireland, to test the feasibility of wind blades as electrical transmission towers (*Re*-Wind 2021; Stone, 2021). Overall, all of these repurposing projects demonstrate the different potential applications of WTB.

4.3. *Recycling pathways*

Over the past century, several efforts have been made by industry, and research to develop different recovery methodologies for polymer matrix fibre-reinforced composites such as mechanical separation (milling, grinding) and thermochemical approaches. Nonetheless, without a proper circular economic model for composite recycling it will be difficult to create business models that can successfully maximise material sustainability and value throughout the material's lifetime. To address this challenge Hagnell and Åkermo (2019) proposed a recyclate value model to establish the future closed-loop material usage of fibre-reinforced composite materials. A closed-loop model for such

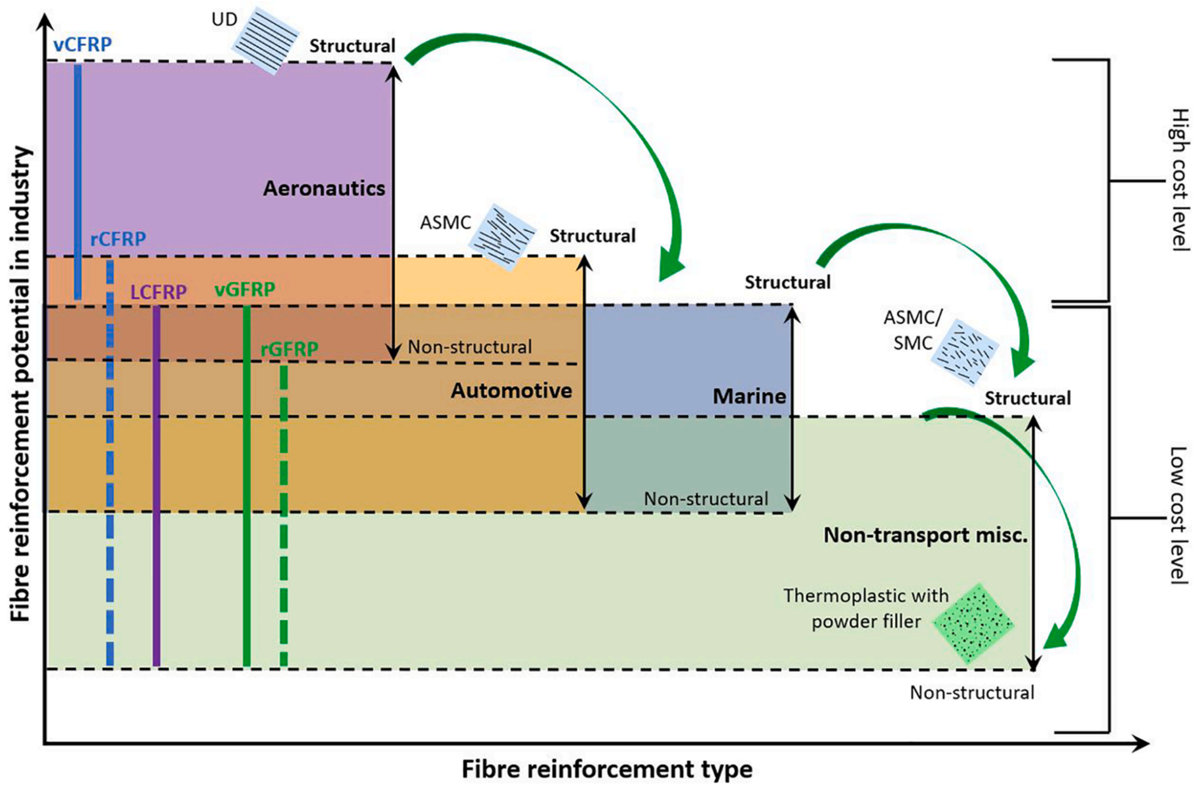

Fig. 11. Relevant applications for researched recycled composite materials together with a conceptual closed loop material flow of the transfer from a structural aeronautical component to a powder-filled thermoplastic component, adapted from (Hagnell and Åkermo, 2019).

materials would help to improve recyclability, resource-efficiency, energy conversion and reduced raw fibre reinforcement costs (Hagnell and Åkermo, 2019).

Hagnell et al's model (Fig. 11) is composed of three recycling cycles. In each recycling cycle the recovered material losses part of its mechanical properties and market value. This leads to potential structural and non-structural uses of the recycled composite materials. Based on the mechanical properties and market value of the reclaimed material Hagnell and Åkermo (2019) identified the number of recycling cycles that carbon fibre and glass fibre should go through before reaching no economic viability. For example, According to Hagnell and Åkermo (2019) results, high-strength carbon fibres can only be recycled once in order to be economically viable, and the recycled material can be used as powder filler. In the case of high-modulus carbon fibre, up to three recycle cycles can be achieved if the recovered material is recycled in fibrous form and reintroduced as fibre-reinforcement. Overall, the results of Hagnell and Åkermo (2019) recyclate value model indicate that approximately 50% material cost reductions can be obtained at equivalent mechanical performance by using recycled fibre instead of virgin fibre in suitable applications. This means that for lightweight applications this cost reduction gives new material choices to design low-cost parts with diverse stiffness. The following sections describe the advantages and disadvantages of the different state-of-the-art recycling methods for FRPC.

4.3.1. *Mechanical recycling*

Mechanical grinding is a mature technology that has been extensively used and investigated for the recovery of raw materials from composites. Mechanical recycling is composed of several mechanical processes such as shredding, crushing, and milling to reduce the size of large components and parts to produce a fibrous or powder product for reuse (Ayre, 2018). Mechanical recycling processes require clean and unpolluted waste material (Bhadra et al., 2017). The downside of this technology is that the resulting fibrous and powder material cannot be reused in thermosetting compounds due to their low mechanical strength and bonding properties with virgin polymer material (Pickering, 2006).

However, the cement industry is well known for absorbing and recycling waste of different kinds (Yang et al., 2018). This provides several opportunities for the end use of WTB as fuel for cement kilns and as aggregate and filler replacements for concrete composites (Conesa et al., 2011). The production of cement requires high levels of energy expenditure due to the high temperature of the kilns (Huntzinger and Eatmon, 2009). Therefore, in an effort to reduce the environmental impact of the incineration of polymer composites, the use of mechanically recycled polymer composites in cement kilns for energy recovery has been proposed (Jacob, 2011). For example, Liu et al. (2015) performed a full-scale test where fibre glass waste was used to replace part of coal used in a cement kiln. They demonstrated that the thermal properties of GF composite waste have a better combustion performance than coal, showing great significance for energy-saving and emission reduction in the cement industry.

Another viable option is to use polymer composite waste as a filler and aggregate for concrete. For example, several studies have demonstrated that mechanically recycled GF composites can improve the mechanical properties of concrete composites (Ribeiro et al., 2015; Asokan et al., 2009; Dehghan et al., 2017). Moreover, the use of mechanically recycled GF composites can reduce roughly 15% of the fine aggregate cost (substitute for sand) (Asokan et al., 2009). However, the limitation of using polymer composite waste as concrete filler is the quality control process, which requires specialised experimental and manufacturing facilities (Asokan et al., 2009).

4.3.2. *Thermal recycling processes*

Three thermal recycling processes can be used for polymeric matrix fibre-reinforced composites: pyrolysis, fluidised-bed pyrolysis, and microwave pyrolysis. These processes focus on the recovery of synthetic fibres at the expense of the polymeric matrix (Bhadra et al., 2017). On the one hand, the advantage of thermal recycling processes over mechanical and chemical recycling processes is that thermal processes are tolerant to contaminated material (Bhadra et al., 2017). On the other hand, the disadvantage of using thermal recycling processes for polymer composites is the deterioration of the mechanical properties of synthetic fibres (Pender and Yang, 2019).

4.3.2.1. Pyrolysis process. Pyrolysis is used to thermally decompose materials at elevated temperatures in an inert atmosphere with some energy recovery. During the pyrolysis process of FRPC, the polymer matrix is degraded into char and gases such as carbon dioxide, hydrogen, and methane, and an oil fraction extracts the synthetic fibres (Fraisse et al., 2022). At the end of the pyrolysis process, the remaining fibres are contaminated with char, and a subsequent post-pyrolysis treatment is required to clean the fibres (Cunliffe and Williams, 2003).

Under typical operational conditions, pyrolysis is detrimental to the mechanical performance of synthetic fibres such as glass (Oliveux et al., 2015). However, according to several studies, under specific operational conditions – preferably low temperatures – it is possible to recover carbon and GFs with mechanical properties similar to virgin material from either thermosetting or thermoplastic polymer composites (Grause et al., 2012; Ginder and Ozcan, 2019; Stoeffler et al., 2013; Lopez-Urionabarrenechea et al., 2020; Onwudili et al., 2016). This makes the pyrolysis process the most viable and promising method not only for effective recovery of high-quality synthetic fibres but also to produce energy (Naqvi et al., 2018). As result, pyrolysis is considered the most successful industrialised technique for material recovery of FRPC (Hagnell and Åkermo, 2019).

4.3.2.2. Fluidized bed process. Fluidized bed is a pyrolysis-based process. This process uses a bed fluidised by hot air to create oxidant environment to rapidly burn materials and produce clean flue gas (Oliveux et al., 2015). For the last 20 years, the University of Nottingham has been investigating the recovery process and future commercial operation of GFs and CFs from thermosetting composites with a fluidised bed at a laboratory scale (Pickering et al., 2015). The fluidised-bed process for thermosetting composites uses bed of silica sand fluidised by air, operating at a temperature close to 500 °C to release synthetic fibres by attrition of the resin (Pickering et al., 2000). The fibres recovered from this process are short, discontinuous, clean fibres (Vijay et al., 2016) with similar mechanical properties to those of virgin fibres (Pickering et al., 2015). This is a contaminant-tolerant process that allows for the processing of dissimilar thermosetting polymers with advantages such as accurate temperature control, operation continuity, and scalability (Pender and Yang, 2019).

More recently, Pender and Yang (2019) have proposed a new fluidised-bed approach to improve thermosetting matrix decomposition and reduce energy input. Pender and Yang (2019) proposed the integration of a CuO nanopowder fluidised-bed system to assist the polymer combustion process. Based on their results, the used of CuO nanopowder as an oxide catalyst significantly accelerated the thermal degradation of epoxy polymers and improved the yield of GFs up to 70%. However, according to Pender and Yang (2019), the process did not increase fibre strength retention.

4.3.2.3. Microwave pyrolysis. Microwave pyrolysis is a thermal degradation process was initially developed in 1995 by Tech-En Ltd. (Hainault, UK) (Holland, 1995). This process uses microwaves to heat a mix of polymer waste and carbon to temperatures close to 1000 °C in an inert atmosphere. During the heating process, carbon acts as a microwave-absorbent material that transfers to the polymer waste the energy absorbed from the microwaves by conduction (Ludlow-Palafox and Chase, 2001; Lam and Chase, 2012). This method has been demonstrated to be an effective method for recovering and recycling the chemicals present in polymer composites, degrading the matrix into gases and oil (Åkesson et al., 2012). The advantages of microwave pyrolysis are as follows: it allows for the recovery of char-free CFs and GFs, without drastically affecting their mechanical properties; the process is energy- and time-efficient; and it requires smaller equipment compared to traditional pyrolysis (McConnell, 2010; Shuaib and Mativenga, 2016).

4.3.3. Chemical recycling processes

Chemical recycling is one of the most economical recycling methods with high levels of material reclamation for high-performance composites (Liu et al., 2004; Job, 2014). Chemical recycling involves the depolymerisation of polymers by chemical degradation through the use of chemical dissolution reagents. The outputs of the chemical recycling processes of polymer composites are clean fibres (carbon or glass) and the depolymerised matrix in the form of monomers or petrochemical feedstock. Chemical recycling processes can be classified into high-temperature solvolysis and low-temperature solvolysis (also called dissolution), and depending on the solvent, they can be further classified as follows: hydrolysis (using water), glycolysis (glycols), and acid digestion (using acid) (Yang et al., 2012). The only limitation associated with these types of recycling processes is their questionable environmental impact, such as widespread water and air pollution and harmful health hazards to workers (Shuaib and Mativenga, 2017). Additionally, despite great advantages of the solvolysis processes they still not used on an industrial scale (Hagnell and Åkermo, 2019).

4.3.3.1. High temperature solvolysis. High-temperature solvolysis consists of a chemical treatment that uses different types of solvents under supercritical conditions (temperature and pressure) such as water to degrade and wash away thermosetting and thermoplastic resins from the fibres of polymer composites (Mattsson et al., 2020). Depending on the nature of the resin, high or low temperatures and pressures are necessary to degrade the resin (Liu et al., 2017). The advantage of high-temperature solvolysis compared to pyrolysis is that it requires lower temperatures (Ayre, 2018). However, at an industrial scale, solvolysis could incur more significant expenses due to the expensive reactors and considerable energy expenditures. Moreover, the environmental impact of chemical recycling remains questionable (Post et al., 2019).

4.3.3.2. Low temperature solvolysis (dissolution). Low-temperature solvolysis, also called dissolution, allows for the recovery of both the polymer matrix and full-length GFs from thermoplastic and thermosetting fibre-reinforced composites. Dissolution is a similar process to high temperature solvolysis; however, it only uses solvents, and it is performed at temperatures <200 °C or at room temperature (Lebedeva et al., 2020). Using this process, it is possible to recover thermosetting composite materials with near 100% recyclability. Moreover, the process can extract CFs with mechanical properties similar to those of virgin fibres, including the epoxy matrix, which can be repolymerised to refabricate composite materials (Yu et al., 2016; Liu et al., 2017). Furthermore, it has been suggested that low-temperature solvolysis can yield more competitive thermoplastic fibre-reinforced composites than thermosetting reinforced composites (Cousins et al., 2019).

Table 5
Summary of advantages and disadvantages of recycling methods (Krauklis et al., 2021; Pickering et al., 2015; Selfrag 2021; Vo Dong et al., 2018; Pickering et al., 2000; Commision, 2015).

Recycling method	Advantages	Disadvantages
Mechanical recycling	• Industrial scale • Low operational costs • Medium investment cost • Low energy consumption • No use of hazardous materials	• Degradation of fibre mechanical properties • Short fibres are recovered
Pyrolysis	• Industrial scale • Medium operational costs • Low investment cost • High retention of fibre mechanical properties • No use of chemical solvents • Tolerance to material contamination • Energy recovery • By-products can be used for production fuels and oils	• High energy consumption • Release of hazardous gases • Fibres contaminated with char and changes in chemical structure • Process difficult to control
Fluidized bed	• Recovery of clean fibres • High tolerance to material contamination • Energy recovery	• Laboratory scale • No resin recovery
Microwave pyrolysis	• Low operational costs • Medium energy consumption • Process easier to control than pyrolysis	• Laboratory scale • High investment cost • Laboratory scale
Solvolysis (super critical water)	• Medium energy consumption • Very high retention of fibre mechanical properties and length • Recovery of clean fibres • The most environmentally friendly method	• Laboratory scale • High operational cost • High investment cost • Low tolerance to material contamination • Potential environmental impact if hazardous solvents are used
High voltage fragmentation	• Industrial scale potential • High retention of fibre tensile strength	• Laboratory scale • Short fibres are recovered • High decrease of modules of glass fibre

4.3.4. *Electrochemical recycling*

Electrochemical recycling, also called high voltage fragmentation, uses high-voltage electrical pulse discharges to disintegrate the polymer matrix of fibre-reinforced composites in a vessel filled with water or electrolytes (Zhu et al., 2019; Zhang et al., 2020). Compared with mechanical recycling, this method allows for the extraction of longer and cleaner recycled fibres (carbon or glass) with a strength retention rate close to 90% (Zhu et al., 2019; Mativenga et al., 2016). However, the drawbacks of this technology are the high energy consumption and the lack of cost competitiveness beyond the laboratory scale (Mativenga et al., 2016; Leißner et al., 2018; Selfrag 2021). The advantages and disadvantages of different recycling methods are presented in Table 5 and in Fig. 12 are presented the materials flows and technical specifications of the discussed recycling systems.

4.3.5. *Current recycling industry initiatives*

The main barriers to recycling WTB are the lack of a market for the recirculated material, the cost of recycling operations WTB (Cherrington et al., 2012), and the lack of practical experience in applying secondary materials to new products (Jensen and Skelton, 2018). Despite these limitations, there is an increase in industry initiatives to develop new business models and technologies to reduce the environmental impact of fibre-reinforced composite materials with different recycling methods and creating new products based on the recovered material.

Several industry efforts are being made in different parts of the world to create successful business models around the recycling of WTB. For example, at the end of 2020, the first large-scale agreement to recycle WTB in the US was signed between Veolia and General Electric (GE). The project will turn WTB into energy and raw material as additives for cement production (Veolia 2020). This agreement will provide the foundations to create a circular economy (CE) for composite materials in the US. According to the environmental impact analysis of the project, the use of composite blades in cement kiln co-processing can provide a reduction of water consumption and CO_2 emissions by 13% and 27%, respectively (Veolia 2020). Moreover, this approach reduces the need to used large quantities of other materials such as coal, silica, limestone, and mineral-based raw materials (Veolia 2020).

In 2021, a collaborative three-year project was announced between ten Danish partners, including LM Wind Power, to establish the commercialisation of the recycling industry for composite WTB (Power, 2021). The project, called 'DecomBlades', focuses on the implementation of recycling technologies and solutions that can be upscaled and applied on a global scale (Power, 2021). The DecomBlades project will address four processes: blade shredding and transport, pyrolysis, co-processing for cement production, and recycling materials into new products (Power, 2021). Another example is the Danish company Miljoskarm. This six-year-old company developed its own technology to specifically crush and recycle WTB and turn them into a variety of noise-shielding products, such as noise-cancelation barrier screens (Fig. 13) (Miljoskarm 2021). Miljoskarm innovative noise-barrier screens are made of an ultra-resistant mix of fibreglass and industrial glue designed to block noise from highways and factories (Miljoskarm 2021).

In the US, Global fibreglass Solutions offers a fibreglass wind turbine blade-recycling service and green-product manufacturing. Its blade-recycling service includes blade dismantling, transport, and recycling. The recycling process involves the creation of recycled raw material such as short-strand fibre glass and EcoPoly pellets that can compete with virgin material products (Solutions, 2021). The company sells and uses its EcoPoly pellets to fabricate its own customised products such as composite panels, railroad ties, and plastic composites (Solutions, 2021). According to Global fibreglass Solutions (Solutions, 2021), its focus is on providing a zero-waste process that avoids the landfilling and incineration of blades by offering a sustainable recycling second life for fibreglass composite material. Eco-Wolf INC, located in Florida, is another company with its own proprietary technology to recycle fibre-reinforced composites. The technology is based on the Seawolf Recycling and Dry Additive System, composed of a mechanical grinder, air-powered metering, and a transportation assembly attachment to a fibreglass spray gun (ECO-WOLF 2020). According to Wolfgang Unger, the creator of this technology, 'this process helps to reclaim the raw material expenses and prevent waste disposal costs, resulting in material cost reduction, environmental impact reduction and an enhanced end product' (Unger, 2020). In this way, Eco-Wolf incorporates up to 35% of recycled fibres with virgin material into new products such as baths, spas, boats, and architectural products (ECO-WOLF 2020). Wolfgang Unger's technology allows for a 20–50% reduction in raw material costs and an 80–100% reduction in labour roll-out. The only disadvantage of Eco-Wolf's approach is that its system is not currently available for direct application to large WTB (ECO-WOLF 2020).

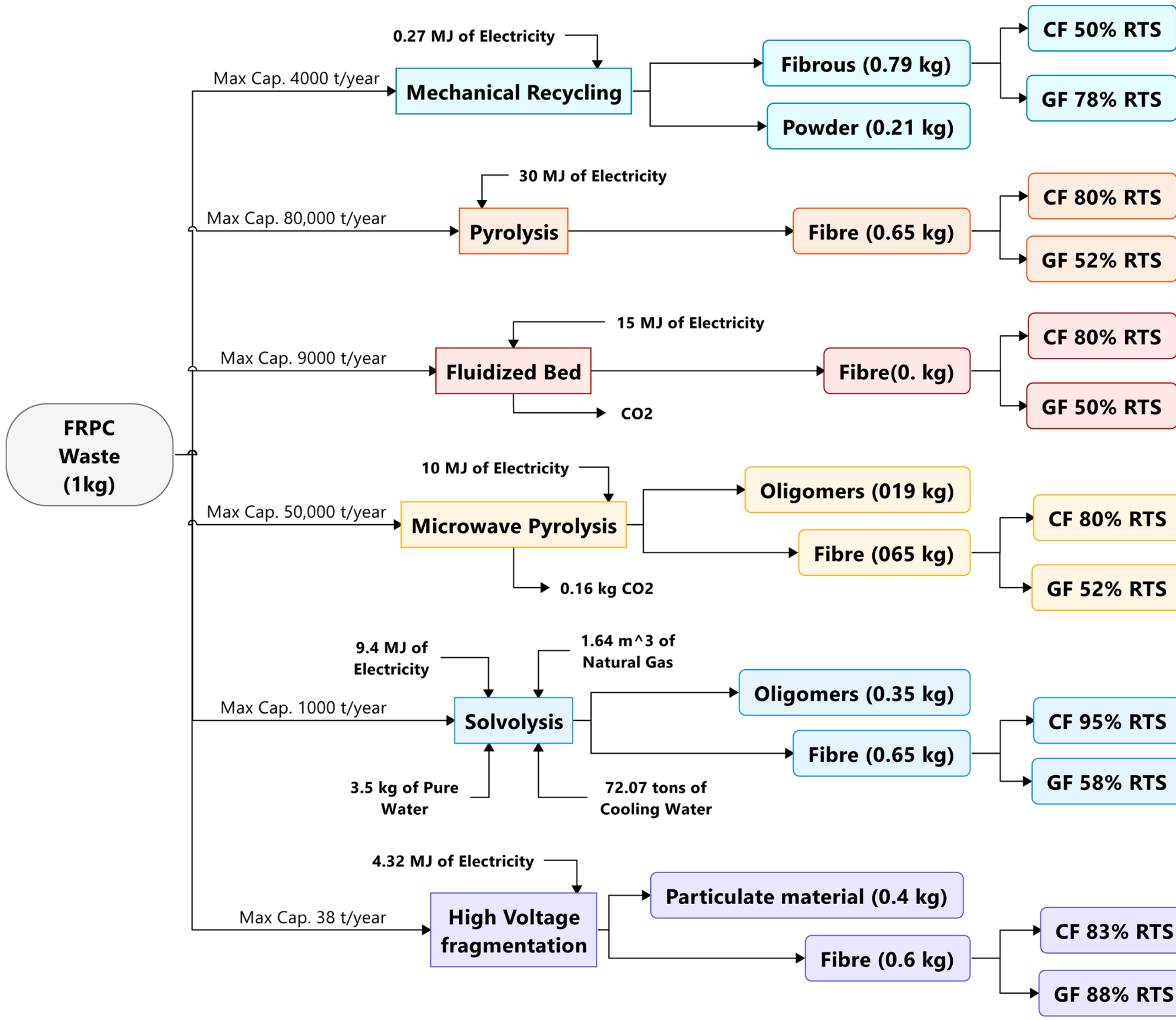

Fig. 12. Materials flows and technical specifications of fibre reinforced polymer composite recycling systems. Cap. = processing capacity, RTS = retained tensile strength (Krauklis et al., 2021; Pickering et al., 2015; Vo Dong et al., 2018; Pickering et al., 2000; Commision, 2015).

In the case of CF composites, ELG Carbon Fibre Ltd, located in the UK, has developed the world's first and largest CF recovery process line, composed of mechanical shredding, pyrolysis, and chopping (Fibre, 2021). According to ELG Carbon Fibre (Fibre, 2021), it is not trying to substitute virgin CFs with a recycled material; its idea is to create a market for its four main types of converted CF products, which are milled fibres, non-woven mats, pellets, and chopped fibres (Fibre, 2021). The ELG recycling plant currently produces more than 1000 tonnes of recycled CF products per year with 95% strength retention and 99% modulus retention (Fibre, 2021). ELG Carbon Fibre states that 'carbon fibre waste can be recovered and converted to new products using less than 10% of the energy required to produce the original carbon fibre, fulfilling legislative and sustainability targets' of the EU (Fibre, 2021).

Another company focused on the recovery of CF from polymer matrix composites is Adherent Technologies Inc. This R&D company has developed a wet-chemical breakdown process called the Jumbo process (Technologies, 2021), which allows for the recovery of 99% clean CFs with mechanical properties 95% close to virgin material (Technologies, 2021). According to Adherent Technologies Inc, the Jumbo process uses off-the-shelf chemical equipment that can easily be scaled up (Technologies, 2021).

4.4. Recovery and disposal strategies

The end service life of WTB currently involves three different pathways: direct deposit in a landfill, incineration, and recycling.

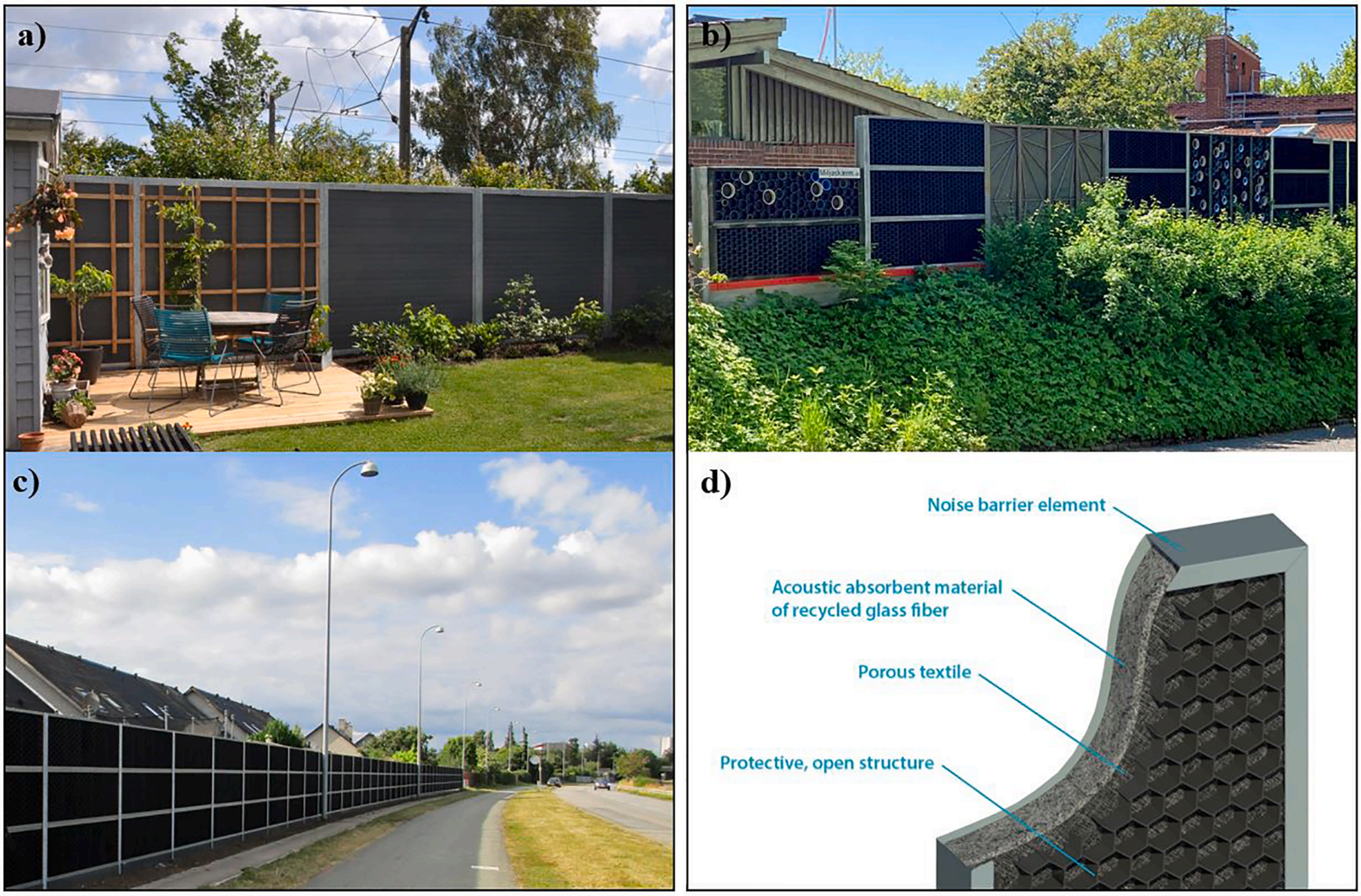

Fig. 13. Miljoskarm products made of recycled WTBs. a) Reflective noise barriers; b) and c) Absorbent noise barriers to reduce traffic noise; d) Cross section of reflective noise barrier, by kind permission of Miljoskarm (2021).

Unfortunately, only 30–40% of fibre-reinforced plastic waste can currently be reused to form new composite materials, with most going to the cement industry as filler material (Larsen, 2009). Moreover, approximately 90% of the fibre reinforced polymer composite material is landfilled. The following sections describe the different environmental impacts caused by landfill and incineration of fibre reinforced polymer composites.

4.4.1. Landfill deposition

Worldwide, landfilling is the most common route to dispose of polymers and their derivative materials; however, it is the least preferred waste management option under the EU's Waste Framework Directive. Moreover, the landfill of composite waste is already forbidden in Germany, and other EU countries are expected to follow suit. The disposal of non-biodegradable polymer composites into landfills creates several environmental and health issues due to various harmful additives and breakdown by-products from the polymer matrix. For example, the leaching of polymer composites' additives and coatings can result in soil and ground water contamination (Bhadra et al., 2017). Moreover, landfill gas is slowly released into the atmosphere and groundwater, contributing to a large portion of the greenhouse effect with further potential adverse effects on public health. Some components of landfill gas are carbon dioxide, methane, volatile organic compounds, hazardous air pollutants, and odorous compounds (Vijay et al., 2016). Thermosetting polymer resins often contain volatile organic compounds that have been linked to cancer and respiratory diseases. Landfill deposition of large parts made of composite polymers is currently not an option in the EU, and in the near future, it will not be possible in many additional countries due to increasing environmental regulations (Jensen and Skelton, 2018). This leaves incineration and recycling as the only two future options for the end service life of WTB.

4.4.2. Incineration and co-incineration

After landfill disposal, incineration is the most common route to dispose of WTB (Larsen, 2009). Incineration involves burning the composite materials in furnaces with air to extract energy from the burning material (Toxicology et al., 2000). For the incineration of wind turbines, they must first be dismantled, crushed, and transported (Larsen, 2009); then, the material is burnt, and the remaining ash content from the incineration process, which is about 50% of the composite, is distributed to a landfill afterward (Murray et al., 2019). In the case of CF composites, incineration requires proper precautions to avoid the release of residual fibres into the environment, which can cause electrical interference issues (Vijay et al., 2016). Despite the wide use of the incineration to dispose of polymer composite materials, it is not a completely environmentally friendly process. The incineration of waste

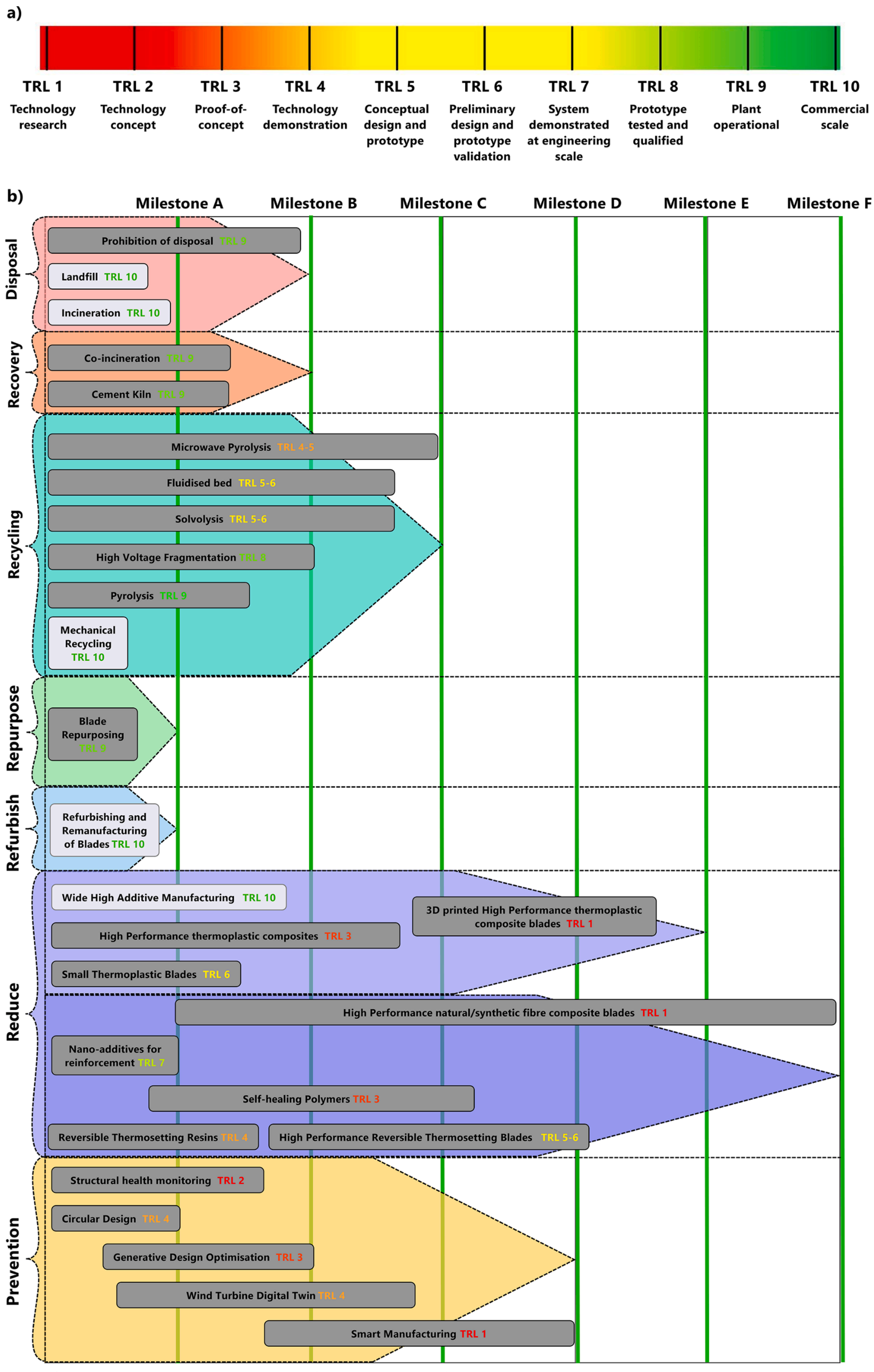

Fig. 14. a) Technology readiness levels for industrial and commercial purposes.; b) Technology roadmap plan for product stewardship solutions for WTB waste, TRLs extracted from (*Schmid* et al., *2020*; *Fitzgerald* et al., *2021*; *Krauklis* et al., *2021*; *Siemens-Gamesa 2021*; *Hagnell and Åkermo, 2019*; *Selfrag 2021*; *Commision, 2015*; *Lerides and Johanna, 2020*; Group, 2016; Mishnaevsky, 2021; Dutchwind 2021; Brown and Stella, 2019; Erikstad, 2017; He and Bai, 2020; Wu et al., 2019; Rybicka et al., 2016; Watson et al., 2019; *Mohamed Sultan* et al., *2017*).

Table 6
Strategies for the technology roadmap for product stewardship solutions for wind turbine blade waste.

Milestone	Duration	Strategies	Requirements	Outcomes
Milestone A: Repurpose and refurbish	4 years	• Introduce architectural principles in university courses to use recovered blades. • Creation of public spaces with recovered WTB. • Governmental incentives for companies dedicated to refurbish and remanufacture of blades.	• Governmental support, incentives and promotion of blade architectural use.	• Full industrialization of repurpose and refurbish circular economy pathways of WTB.
Milestone B: Disposal and Recovery	9 years	• Progressive increase of disposal and incineration rates. • Increase taxes for disposal and incineration of FRPC. • Promote the use of co-incineration and cement kiln of FRPC.	• Global governmental policies to band disposal and incineration of FRPC. • Band of disposal and incineration of FRPC by 2030.	• Global prohibition of disposal and incineration of FRPC. • Full industrialization of pyrolysis and high voltage fragmentation for FRPC. • Full industrialization of co-incineration and cement kiln of FRPC.
Milestone C: Recycling	14 years	• Governmental support for pyrolysis and high voltage fragmentation for FRPC. • Accelerate industrialization of solvolysis, microwave pyrolysis, and fluidised bed recycling by facilitating industry-research collaboration. • Governmental support for creation of new business dedicated to the recovery and use of materials from recycled FRPC. • Establishing applications for FRPC recycled material.	• Establishment of on-site blade fragmentation plants. • Establishment of industry standards for FRPC recycling technologies. • Establishment of industry standards for FRPC recycled materials. • Creation of robust recycling economic models for FRPC recycled materials and technologies.	• Establishment of a global circular economy system for recycled materials from FRPC.
Milestone D: Prevention	19 years	• Encouragement and support for industry to adopt WTB biomimicry, generative and circular design approaches. • Adopt rapid high-resolution damage/repair screening technologies from aerospace. • Develop affordable multi sensor technologies (miniature/nano) and algorithms for rapid and reliable detection of different types of blade damage. • Demonstrate in-line diagnostics for production of WTB. • Deploy simulation tools with for multi-physics phenomena involved in WTB supply chain, manufacturing, operation, and recycling.	• Establishment of industry standards for digital twin creation and maintenance. • Establishment of industry standards for circular design practices. • Collaboration between all supply chain actors towards industry 4.0 technologies. • Accrediting companies with eco-friendly certificate.	• Establishment of closed loop digital twin systems for design, manufacturing, and maintenance of WTB. • Establishment of closed loop digital twin systems of WTB recycling technologies.
Milestone E: Reduce	24 years	• Design modular WTB for affordable transport and installation. • Support workforce development programs in AM. • Create AM models for composite blade mould tooling. • Development of new AM technologies to create void free FRPC WTB. • Capital investment in WHAM technologies for fabrication of FRPC WTB	• Establishment of industry standards for AM of high performance FRPC.	• Establishment of high-performance AM WTB. • Revolution in blade design (lighter and stronger blades) by combining the outcomes from milestone D with AM and WHAM.
Milestone F: Reduce	29 years	• Improve natural fibre-resin adhesion with fibre treatments and nano additives. • Collaboration between industries to share best practices and technologies in high performance reversible FRPC. • Government support to accelerate industrialization of high performance reversible FRPC and natural FRPC.	• Implementation of carbon tax on non-reversible thermosetting resins • Establishment of industry standards for high performance natural and hybrid FRPC. • Establishment of industry standards for high performance reversible FRPC. • Accrediting companies with eco-friendly certificate.	• 100% fibre recovery from WTB with 100% retention properties and length. • Establishment of a global circular economy system for high performance reversible WTB. • Establishment of a global circular economy system for high performance WTB made of natural and hybrid FRPC.

releases greenhouse gases (such as CO2), which contribute to climate change, including toxic emissions that represent hazards to human health and the environment (Cormier et al., 2006; Rowat, 1999). Moreover, the different activities that are required for this process place further strain on the environment in terms of energy usage and emissions (Murray et al., 2019). Furthermore, the incineration of composite materials is not always possible. For example, incinerating large parts such as WTB could be cost prohibitive, and GF residue can cause process stoppages (Jacob, 2011).

Co-incineration is a better alternative than incineration. This process counteracts some of the disadvantages of the incineration allowing energy and material recovery (Vo Dong et al., 2018). The co-incineration recovers material in the form of ash, which accounts for 30–35 wt% (Polettini et al., 2001), to be used as filler for cement composite preparation (Li et al., 2012; Aubert et al., 2006). In co-incineration the energy recovered by the combustion fibre reinforced polymer composite waste can reduce the amount of coal used in the combustion furnace. This approach can aid in the reduction of CO_2 emissions as well as the minimisation of the consumption of natural materials (Yang et al., 2018; Li et al., 2012).

5. Roadmap of strategies

Roadmapping is defined as the strategic process of determining the trajectories to follow to reach future success towards a desired destination (Daim and Oliver, 2008). There are three technology states that a technology roadmap should illustrate, these are: the current state of technologies, a desirable future state, and strategies to reach the future state (Sarvari et al., 2017). To better understand the current state of a specific technology in relation to its maturity the most widely used tool is the technology readiness level (TRL) scale (Conrow, 2011). This tool was first developed by NASA in the 1970′s to allow more effective assessment and communication regarding the maturity of new technologies (NASA 2012). The NASA's TRL tool is a nine-level rating scale stating in TRL 1 with the lowest maturity level to TRL 9 that corresponds to a fully matured technology (Olechowski et al., 2015). However, the NASA TRL nine scale does not consider the readiness for industrial and commercial purposes. Therefore, to provide a more realistic TRL for industrial and commercial purposes the NASA's TRL has been expanded to included one additional level to represent that a specific technology is commercially ready, as shown in Fig. 14a (Collins and Pincock, 2010; Straub, 2015).

Until this point, we had presented a variety of potential technologies and pathways that can help to address the environmental issues of the disposal of FRPC material from WTB. Nonetheless, some of the presented technologies still in development have not reached commercial stages or have not been integrated. Hence, we the feel the need to present a technology roadmap based on the technology readiness level of the presented technologies to envision a project plan to the different stakeholders that can directly or indirectly positively influence the maturation and adoption of solutions for the management of waste of FRPC from WTB. The proposed roadmap plan (Fig. 14b) is composed of 6 milestones starting from the year 2021 until 2050. Moreover, we developed a series of strategies, requirements and outputs to achieve the proposed milestones, as presented in Table 6.

6. Discussion

We have presented the concept of integrated product stewardship and its pathways for WTB emphasising that only by integrating these with Industry 4.0 technologies will it be possible to fully manage and control the whole life cycle in a sustainable manner. Moreover, to achieve such an endeavour, governments, industry, and academia need to work in close collaboration to identify in more detail the economics and the feasibility of the presented pathways and their technologies. For this purpose, the next step of this study is to create different system dynamics simulation models of the proposed product stewardship pathways of the leading countries in wind energy. These models can provide a better understanding of the dynamic complexities inherent in the wind energy sector and the technologies presented in this study (Suprun, 2018; Naill, 1992; Shen et al., 2009).

A system dynamics simulation model can also reveal how government policies and supportive programs can help to accelerate the development of key technologies to address the environmental impact of WTB by 2050 (Jeon and Shin, 2014). The identification of stable and predictable policies that encourage collaboration between industry and government is vital to provide confidence, reduce technology development costs, and ensure a long-term sustainable development. Governments need to create and maintain policy targets to better manage polymeric material waste for green growth and increase policy support for cost-effective technologies by providing incentives and finance for firms to deploy emerging technologies. For this purpose, system dynamics simulation models can provide a better understanding of the dynamic complexities inherent in the wind energy sector specially in countries with lack of policy support such as the United States, Australia and China. Wind power is a highly globalized industry in which close collaboration is essential (GWEC 2020). International coordination mechanisms must be established for technical and industrial standards to minimize WTB waste and facilitate technology exchange.

7. Conclusion

In response to the potential environmental crisis that can result from the incoming waste generated by the disposal of WTB, this study proposes an integrated product stewardship approach for WTB. The proposed approach brings together the different actors, stakeholders, economic and technological factors to set the foundations for a high-level management strategy for global environmental collaboration to address this issue. For this purpose, the different states of the technologies, materials, designs, and recycling solutions that can help to mitigate this environmental problem were explored, including the various industry efforts that have been made to address the problem. Having this in mind, a technology roadmap and strategy plan were proposed with the different potential circular economy pathways currently available taking into consideration the TRL of the discussed technologies.

Nonetheless, further studies and simulations with different scenarios are required to quantify the most feasible pathways for the numerous stakeholders involved. Moreover, to achieve the proposed endeavour, strong governmental support is necessary to create appropriate industry standards, accelerate development of technologies with industrial potential, and finally industry must acquire practical experience.

Author contributions

Conceptualisation: D.M-M., and R.A.S.; Formal analysis: D.M-M., R.A.S., W.H., N.F., P.W., and H.W.; Funding acquisition: R.A.S.; Investigation: D.M-M.; Methodology: D.M-M. and R.A.S.; Project administration: D.M-M. and R.A.S.; Resources: D.M-M.; Supervision: D.M-M., R.A.S., W.H., N.F., P.W., and H.W.; Visualisation: D.M-M.; Writing—original draft: D.M-M.; Writing—review & editing: D.M-M., R.A.S., W.H., N.F., P.W., and H.W..

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Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A

Table A1

Table A1
Classification of selected studies.

Ref	Cod	Year	Location	Prevention	Reduction	Refurbish	Repurpose	Recycling	Reuse	Disposal	TRL	Industry
(Schmid et al., 2020)	S1	2020	EU	✔			✔	✔	✔		✔	✔
(Gharfalkar et al., 2015)	S2	2015	UK	✔	✔			✔	✔	✔		
(Tao et al., 2018)	S3	2018	China	✔								
(Güemes et al., 2020)	S4	2020	Spain	✔	✔							
(Theiler et al., 2017)	S5	2017	Germany	✔								
(Azhar, 2011)	S6	2011	USA	✔								
(Wang et al., 2018)	S7	2018	China	✔								
(Lu et al., 2019)	S8	2019	UK	✔								
(Pan and Zhang, 2021)	S9	2021	Singapore	✔								
(Erikstad, 2017)	S10	2017	Norway	✔								
(Tao et al., 2019)	S11	2019	China	✔								
(Aheleroff et al., 2021)	S12	2021	New Zealand	✔								
(Condemi et al., 2019)	S13	2019	Italy	✔				✔	✔	✔		
(Wang et al., 2020)	S14	2020	China	✔		✔						✔
(Tao and Qi, 2019)	S15	2019	China	✔								
(Pimenta et al., 2020)	S16	2020	Portugal	✔								
(Kaur et al., 2019)	S17	2020	UAE	✔								
(Tao et al., 2019)	S18	2019	China	✔								
(Qi and Tao, 2018)	S19	2018	China	✔								✔
(Morthorst, 2021)	S20	2009	Denmark	✔								
(Stephenson, 2011)	S21	2011	USA	✔								
(GCube 2014)	S22	2014	UK	✔								
(Chou et al., 2013)	S23	2013	Taiwan	✔								
(McGugan and Mishnaevsky, 2020)	S24	2020	Denmark	✔								
(Gatti, 2019)	S25	2019	Italy	✔								
(Gómez et al., 2020)	S26	2020	Spain	✔								
(Diamanti and Soutis, 2010)	S27	2010	UK	✔								
(Du et al., 2020)	S28	2020	China	✔								
(Solimine et al., 2020)	S29	2020	USA	✔								
(Kusiak et al., 2013)	S30	2013	USA	✔								
(Ciang et al., 2008)	S31	2008	Korea	✔								
(Hameed et al., 2009)	S32	2009	Korea	✔								
(Li et al., 2015)	S33	2015	China	✔								
(Schubel et al., 2013)	S34	2013	UK	✔								
(Rizk et al., 2020)	S35	2020	Canada	✔								
(Brøndsted et al., 2005)	S36	2005	Denmark		✔							
(Swolfs, 2017)	S37	2017	Belgium	✔	✔							
(Mishnaevsky et al., 2017)	S38	2017	Denmark	✔	✔			✔				✔
(Babu et al., 2006)	S39	2006	India		✔							
(Sakellariou, 2018)	S40	2018	USA		✔	✔		✔	✔	✔		✔
(Thomas and Ramachandra, 2018)	S41	2018	India		✔			✔				
(Kalkanis et al., 2019)	S42	2019	Greece		✔			✔				
(Jureczko et al., 2005)	S43	2005	Poland		✔							
(Gowda et al., 2018)	S44	2018	India		✔							
(Collier and Ashwill, 2011)	S45	2011	USA		✔							
(Shrivastava, 2018)	S46	2018	USA		✔							
(Landesmann et al., 2015)	S47	2015	Brazil		✔							
(Beauson et al., 2016)	S48	2016	Denmark		✔			✔				
(Batabyal et al., 2018)	S49	2018	India		✔							
(Elanchezhian et al., 2014)	S50	2014	India		✔							
(Huang, 2009)	S51	2009	USA		✔							
(Naqvi et al., 2018)	S52	2018	The Netherlands		✔	✔		✔	✔		✔	✔
(Jensen and Skelton, 2018)	S53	2018	Denmark		✔		✔	✔	✔	✔		✔
(Caglio, 2019)	S54	2019	Italy		✔	✔		✔	✔			
(Cousins et al., 2019)	S55	2019	USA		✔			✔			✔	✔
(Perry et al., 2012)	S56	2012	France		✔			✔				
(Cherrington et al., 2012)	S57	2012	UK		✔			✔		✔		✔
(Cromwell et al., 2015)	S58	2015	USA	✔	✔							
(Wang et al., 2018)	S59	2018	China		✔			✔				
(Wang et al., 2019)	S60	2019	China		✔			✔				
(Yang et al., 2021)	S61	2021	China		✔			✔				
(Lejeail and Fischer, 2021)	S62	2021	The Netherlands		✔			✔				
(Yuan et al., 2017)	S63	2017	China		✔			✔				
(Liu et al., 2019)	S64	2019	China		✔			✔				
(Post et al., 2019)	S65	2020	The Netherlands		✔			✔	✔			
(Paolillo et al., 2021)	S66	2021	Italy	✔	✔							
(Zhang, 2020)	S67	2020	USA	✔	✔							
(Urdl et al., 2017)	S68	2017	Austria	✔	✔							
(Kim and Yoshie, 2018)	S69	2018	Japan	✔	✔							

(*continued on next page*)

Table A1 (*continued*)

Ref	Cod	Year	Location	Prevention	Reduction	Refurbish	Repurpose	Recycling	Reuse	Disposal	TRL	Industry
(Mphahlele et al., 2017)	S70	2017	South Africa	✔	✔							
(Arun Kumar Koralagundi et al., 2017)	S71	2017	USA	✔	✔							
(Arun Kumar Koralagundi et al., 2015)	S72	2015	USA		✔							
(Shen et al., 2019)	S73	2019	China	✔	✔							
(Shen et al., 2019)	S74	2019	China	✔	✔							
(Shen et al., 2020)	S75	2020	China	✔	✔							
(Zako and Takano, 1999)	S76	1999	Japan	✔	✔							
(Lv and Chen, 2013)	S77	2013	China	✔	✔							
(Khan et al., 2020)	S78	2020	USA	✔	✔			✔	✔			
(Greene et al., 2022)	S79	2015	USA		✔			✔				
(Bruijn and van Hattum, 2020)	S80	2020	The Netherlands		✔			✔				
(Murray et al., 2021)	S81	2021	USA		✔			✔				✔
(Manap et al., 2020)	S82	2020	Malaysia		✔							
(Murray et al., 2017)	S83	2017	USA		✔			✔				✔
(Bhudolia et al., 2020)	S84	2020	Singapore		✔							✔
(Murray et al., 2019)	S85	2019	USA		✔			✔	✔	✔		✔
(Mrowiec, 2018)	S86	2018	Poland		✔			✔	✔			
(Ramesh et al., 2017)	S87	2017	India		✔							
(Tholibon et al., 2019)	S88	2019	Malaysia		✔							
(Sanivada et al., 2020)	S89	2020	Portugal		✔							
(Pantaloni et al., 2020)	S90	2020	France		✔							
(Guduru and Srinivasu, 2020)	S91	2020	India		✔							
(Pop et al., 2020)	S92	2020	Romania		✔							
(Loureiro et al., 2014)	S93	2014	Portugal		✔							
(Tang et al., 2020)	S94	2020	USA		✔							
(Encisoet al., 2020)	S95	2020	Spain		✔			✔				
(Pantaloni et al., 2020)	S96	2021	France		✔							
(Larguech et al., 2020)	S97	2020	Tunisia		✔							
(Bravo et al., 2018)	S98	2017	Canada		✔							
(Jagadeesh et al., 2017)	S99	2017	South Africa		✔							
(Yahaya et al., 2014)	S100	2014	Malaysia		✔							
(Mohammad and Mohamed, 2018)	S101	2018	Malaysia		✔			✔				
(Fitzgerald et al., 2021)	S102	2021	UK		✔			✔			✔	✔
(Khalil et al., 2012)	S103	2012	Malaysia		✔							
(Perremans et al., 2018)	S104	2018	Belgium		✔							
(Wang et al., 2015)	S105	2015	China		✔							
(Asim et al., 2015)	S106	2015	Malaysia		✔							
(Nayak et al., 2019)	S107	2019	India		✔							
(Uma Maheswari et al., 2008)	S108	2008	India		✔							
(Ali, 2011)	S109	2011	Bangladesh		✔							
(Hossain et al., 2014)	S110	2014	USA		✔							
(Bachtiar et al., 2009)	S111	2010	Malaysia		✔							
(Ishak et al., 2012)	S112	2011	Malaysia		✔							
(Krauklis et al., 2021)	S113	2021	Latvia		✔			✔	✔	✔	✔	✔
(Lau et al., 2018)	S114	2018	Australia		✔							
(Jawaid et al., 2011)	S115	2011	Malaysia		✔							
(Mishra et al., 2020)	S116	2020	Czech Republic		✔							
(Jawaid and Khalil, 2011)	S117	2011	Malaysia		✔			✔				
(Sapiai et al., 2020)	S118	2020	Malaysia		✔							
(Belfkira et al., 2020)	S119	2021	Morocco		✔							
(Njuguna et al., 2008)	S120	2008	UK		✔							
(ISO 2015)	S121	2021	Switzerland		✔							
(Ferreira et al., 2018)	S122	2018	Brazil		✔							
(Wang et al., 2020)	S123	2020	China		✔							
(Bhattacharya, 2016)	S124	2016	USA		✔							
(Li et al., 2019)	S125	2018	China		✔							
(Kozlov et al., 2019)	S126	2019	Russia		✔							
(Hasan et al., 2014)	S127	2014	Serbia		✔							
(Marquis et al., 2011)	S128	2011	France		✔							
(Khanam et al., 2015)	S129	2015	Qatar		✔			✔				
(Kausar et al., 2017)	S130	2017	Pakistan		✔							
(Matadi Boumbimba et al., 2017)	S131	2017	France		✔			✔				
(Mechin et al., 2020)	S132	2020	France		✔							
(Sun et al., 2018)	S133	2018	China		✔							
(Devnani and Sinha, 2019)	S134	2019	India		✔							
(Begum et al., 2020)	S135	2020	Australia		✔			✔				
(Joseph et al., 2020)	S136	2020	India		✔							
(Vijay Kumar et al., 2019)	S137	2019	Singapore	✔	✔						✔	
(Oksman et al., 2016)	S138	2016	Sweden		✔						✔	

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Table A1 (*continued*)

Ref	Cod	Year	Location	Prevention	Reduction	Refurbish	Repurpose	Recycling	Reuse	Disposal	TRL	Industry
(Šupová et al., 2011)	S139	2011	Czech Republic		✔							
(Veazey et al., 2017)	S140	2016	USA		✔							
(Veers et al., 2003)	S141	2003	USA		✔							
(van Oosterom et al., 2019)	S142	2019	New Zealand		✔							
(Schubel, 2010)	S143	2010	UK		✔							
(Ong et al., 1999)	S144	1999	USA		✔							
(Camanho and Matthews, 1997)	S145	1997	UK	✔	✔							
(*Post* et al., *2017*)	S146	2017	USA		✔							✔
(Smith, 2000)	S147	2000	USA		✔							
(ISO/ASTM 2015)	S148	2015	USA		✔							
(Ferreira et al., 2017)	S149	2017	Portugal		✔							
(Tofail et al., 2018)	S150	2018	Ireland		✔						✔	
(Hollister et al., 2018)	S151	2018	USA		✔							
(Esmaeilian et al., 2016)	S152	2016	USA		✔	✔						
(Zhong et al., 2017)	S153	2017	New Zealand		✔							
(Dennis, 2007)	S154	2007	USA		✔							
(Reeves, 2008)	S155	2008	UK		✔							
(Momeni et al., 2019)	S156	2019	USA		✔						✔	✔
(*Liu, 2011*)	S157	2011	China	✔	✔							
(Liu and Zhang, 2010)	S158	2010	China	✔	✔							
(Wangyu et al., 2022)	S159	2006	China		✔							
(Murdy et al., 2021)	S160	2021	USA		✔			✔			✔	
(Peeters et al., 2017)	S161	2017	Belgium		✔							
(Garate et al., 2018)	S162	2018	Argentina		✔			✔			✔	
(Khakpour Nejadkhaki and Hall, 2018)	S163	2018	USA		✔							
(Bassett et al., 2015)	S164	2015	Canada		✔						✔	
(Siemens-Gamesa 2021)	S165	2021	Spain		✔			✔			✔	✔
(EireComposites 2021)	S166	2021	Ireland		✔			✔			✔	✔
(Power, 2021)	S167	2021	Denmark		✔			✔			✔	✔
(Camozzi 2021)	S168	2021	Italy & USA		✔						✔	✔
(Post et al., 2020)	S169	2019	USA		✔						✔	✔
(Environment, 2016)	S170	2016	Scotland			✔		✔				✔
(Ortegon et al., 2013)	S171	2013	USA			✔						✔
(Duchwind 2021)	S172	2021	The Netherlands			✔						✔
(Armstrong et al., 2005)	S173	2005	USA	✔	✔	✔						
(Ostachowicz et al., 2016)	S174	2016	Poland	✔		✔	✔	✔	✔	✔		✔
(Katnam et al., 2015)	S175	2015	UK	✔		✔						
(Medici et al., 2020)	S176	2020	The Netherlands				✔		✔			✔
(Alshannaq et al., 2019)	S177	2019	USA				✔		✔			✔
(Bank et al., 2018)	S178	2018	USA				✔	✔	✔			✔
(Joustra et al., 2021)	S179	2021	The Netherlands				✔	✔	✔			✔
(Studio, 2021)	S180	2021	The Netherlands				✔					✔
(Studios, 2021)	S181	2021	The Netherlands				✔					✔
(Guzzo, 2019)	S182	2019	The Netherlands				✔					✔
(Eilers, 2020)	S183	2020	Denmark				✔					✔
(*Re*-Wind 2021)	S184	2020	Ireland & USA				✔					✔
(*Re*-Wind 2018)	S185	2018	Ireland & USA				✔					✔
(Stone, 2021)	S186	2021	USA				✔					✔
(Hagnell and Åkermo, 2019)	S187	2019	Sweden					✔			✔	✔
(Ayre, 2018)	S188	2018	UK					✔	✔		✔	✔
(Bhadra et al., 2017)	S189	2017	Qatar					✔	✔	✔		
(Pickering, 2006)	S190	2006	UK					✔			✔	✔
(Yang et al., 2018)	S191	2018	China					✔	✔	✔		
(Conesa et al., 2011)	S192	2011	Spain					✔	✔			
(Huntzinger and Eatmon, 2009)	S193	2009	USA					✔				
(Jacob, 2011)	S194	2011	EU					✔	✔	✔		✔
(Liu et al., 2015)	S195	2015	China					✔	✔			
(Ribeiro et al., 2015)	S196	2015	Portugal					✔	✔			
(Asokan et al., 2009)	S197	2009	UK					✔				
(Dehghan et al., 2017)	S198	2017	Canada					✔				
(Pender and Yang, 2019)	S199	2019	UK					✔				
(Fraisse et al., 2022)	S200	2016	Denmark					✔				
(Cunliffe and Williams, 2003)	S201	2003	UK					✔				
(Oliveux et al., 2015)	S202	2015	UK					✔	✔			✔

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Table A1 (*continued*)

Ref	Cod	Year	Location	Prevention	Reduction	Refurbish	Repurpose	Recycling	Reuse	Disposal	TRL	Industry
(Grause et al., 2012)	S203	2012	Japan					✔				
(Ginder and Ozcan, 2019)	S204	2019	USA					✔				
(Stoeffler et al., 2013)	S205	2013	Canada					✔				
(Lopez-Urionabarrenechea et al., 2020)	S206	2020	Spain					✔			✔	
(Onwudili et al., 2016)	S207	2016	UK					✔				
(Pickering et al., 2015)	S208	2015	UK					✔				
(Pickering et al., 2000)	S209	2000	UK					✔	✔			
(Vijay et al., 2016)	S210	2016	India					✔	✔	✔	✔	
(Holland, 1995)	S211	1995	USA					✔				
(Ludlow-Palafox and Chase, 2001)	S212	2001	UK					✔			✔	
(Lam and Chase, 2012)	S213	2012	Malaysia					✔	✔		✔	
(Åkesson et al., 2012)	S214	2012	Sweden					✔			✔	✔
(McConnell, 2010)	S215	2010	USA					✔			✔	✔
(Shuaib and Mativenga, 2016)	S216	2016	UK					✔				
(Liu et al., 2004)	S217	2004	China					✔				
(Job, 2014)	S218	2014	UK					✔				✔
(Yang et al., 2012)	S219	2012	The Netherlands					✔			✔	✔
(Shuaib and Mativenga, 2017)	S220	2017	UK					✔				
(Mattsson et al., 2020)	S221	2020	Sweden					✔			✔	
(Liu et al., 2017)	S222	2017	UK					✔	✔		✔	
(Lebedeva et al., 2020)	S223	2020	Russia					✔				
(Yu et al., 2016)	S224	2016	USA					✔				
(Liu et al., 2017)	S225	2017	USA					✔	✔			
(Zhu et al., 2019)	S226	2019	China					✔			✔	
(Zhang et al., 2020)	S227	2020	Australia					✔			✔	
(Mativenga et al., 2016)	S228	2016	UK					✔			✔	
(Leißner et al., 2018)	S229	2018	Germany					✔			✔	
(Selfrag 2021)	S230	2021	Switzerland					✔			✔	
(Vo Dong et al., 2018)	S231	2018	France					✔	✔	✔		
(Pickering et al., 2000)	S232	2000	UK					✔				
(Commision, 2015)	S233	2015	Switzerland					✔			✔	✔
(Veolia 2020)	S234	2020	USA					✔				✔
(Veolia 2020)	S235	2020	USA					✔	✔			✔
(Power, 2021)	S236	2021	Denmark					✔				✔
(Miljoskarm 2021)	S237	2021	Denmark					✔				✔
(Solutions, 2021)	S238	2021	USA					✔				✔
(ECO-WOLF 2020)	S239	2020	USA					✔				✔
(Unger, 2020)	S240	2020	USA					✔				✔
(Fibre, 2021)	S241	2021	UK					✔				✔
(Technologies, 2021)	S242	2021	USA					✔				✔
(Larsen, 2009)	S243	2009	USA					✔	✔	✔		
(Toxicology et al., 2000)	S244	2000	USA						✔	✔		
(Cormier et al., 2006)	S245	2006	USA						✔	✔		
(Rowat, 1999)	S246	1999	Canada						✔	✔		
(Polettini et al., 2001)	S247	2001	Italy						✔	✔		
(Li et al., 2012)	S248	2012	China						✔	✔		
(Aubert et al., 2006)	S249	2006	France						✔	✔		
(Daim and Oliver, 2008)	S250	2008	USA								✔	
(Sarvari et al., 2017)	S251	2018	Turkey								✔	
(Conrow, 2011)	S252	2011	USA								✔	
(NASA 2012)	S253	2021	USA								✔	
(Olechowski et al., 2015)	S254	2015	USA								✔	
(Collins and Pincock, 2010)	S255	2010	USA								✔	
(Straub, 2015)	S256	2015	USA								✔	
(Lerides and Johanna, 2020)	S257	2020	Spain			✔		✔	✔		✔	✔
(Group, 2016)	S258	2016	USA					✔	✔		✔	
(Mishnaevsky, 2021)	S259	2021	Denmark	✔	✔	✔		✔	✔	✔	✔	✔
(Dutchwind 2021)	S260	2021	The Netherlands			✔					✔	✔
(Brown and Stella, 2019)	S261	2019	UK					✔	✔		✔	✔
(Erikstad, 2017)	S262	2017	Norway	✔							✔	
(He and Bai, 2020)	S263	2020	China	✔	✔						✔	
(Wu et al., 2019)	S264	2019	China	✔							✔	
(Rybicka et al., 2016)	S265	2016	UK					✔			✔	
(Watson et al., 2019)	S266	2019	The Netherlands								✔	
(Mohamed Sultan et al., 2017)	S267	2017	UK					✔			✔	

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