WIND TURBINE BLADE WASTE MANAGEMENT: A REVIEW

Laís Madureira Dantas

Thesis presented to the School of Technology and Management in the scope of the Master in Renewable Energy and Energetic Efficiency

Supervisor: Luis Frölén Ribeiro

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“I gave my blood, sweat, and tears for this”

– Taylor Swift

ABSTRACT

Wind energy is in constant growth and over time the installed power of the turbines has increased, as well as its size, due to the development of technology associated.

The blades lifetime is around 20-25 years and wind farms are being decommissioned. Only taking into consideration Europeans offshore wind farms, it is expected to have more than 375,000 tons of wind turbine blades by 2043.

In 2009 some researches were published, arising the concern about the situation and explaining the blades recyclability difficulty, also mentioning some possible end of life routes for the blades.

Most blades are landfilled, which is the last preferred route in the waste hierarchy defined by the European's Waste Directive.

This thesis presents a literature review regarding the wind turbine blade waste management, comprehending the environmental impact associated with the wind energy. The review was done searching for published articles in two data bases: Scopus and Web of Science, applying a set of different keywords to make the search. A total of 849 articles were found and three selection criteria were applied, resulting in 69 articles selected for this thesis.

The main conclusion is that many published works states basically the same and, although many studies and projects were developed, until now there is no defined solution and route to this material.

Keywords: Wind turbine blade, waste, recycling, end of life, wind turbine

RESUMO

A energia eólica está em constante crescimento e ao longo do tempo a potência instalada das turbinas tem aumentado, bem como a sua dimensão, devido ao desenvolvimento da tecnologia associada.

A vida útil das pás é de cerca de 20 a 25 anos e os parques eólicos estão sendo desativados. Considerando apenas os parques eólicos offshore europeus, espera-se que haja mais de 375.000 toneladas de pás de turbinas eólicas até 2043.

Em 2009 foram publicadas algumas pesquisas, levantando a preocupação com a situação e explicando a dificuldade de reciclabilidade das pás, mencionando também alguns possíveis caminhos de fim de vida das pás.

A maioria das pás é depositada em aterro, que é a última rota preferida na hierarquia de resíduos definida pela Diretiva Europeia de Resíduos.

Esta tese apresenta uma revisão de literatura a respeito do gerenciamento de resíduos de pás de turbinas eólicas, compreendendo o impacto ambiental associado à energia eólica. A revisão foi feita buscando artigos publicados em duas bases de dados: Scopus e Web of Science, aplicando um conjunto de palavras-chave diferentes para fazer a busca. Foram encontrados 849 artigos e aplicados três critérios de seleção, resultando em 69 artigos selecionados para esta tese.

A principal conclusão é que muitos trabalhos publicados afirmam basicamente o mesmo e, embora muitos estudos e projetos tenham sido desenvolvidos, até o momento não há solução e caminho definidos para este material.

Palavras-chave: Pá de turbina eólica, resíduos, reciclagem, fim de vida, aerogerador

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1. INTRODUCTION

Considered to be a green and renewable energy, since it is provided from natural sources and its use does not release greenhouse gas, the wind energy is having a considerable growth, and it is expected to grow by 15% on average per year for the next five years (2022 – 2027) [1].

Since 2001 the wind energy is having a considerable growth, and Figure 1 presents its historic development of installations through the last 21 years.

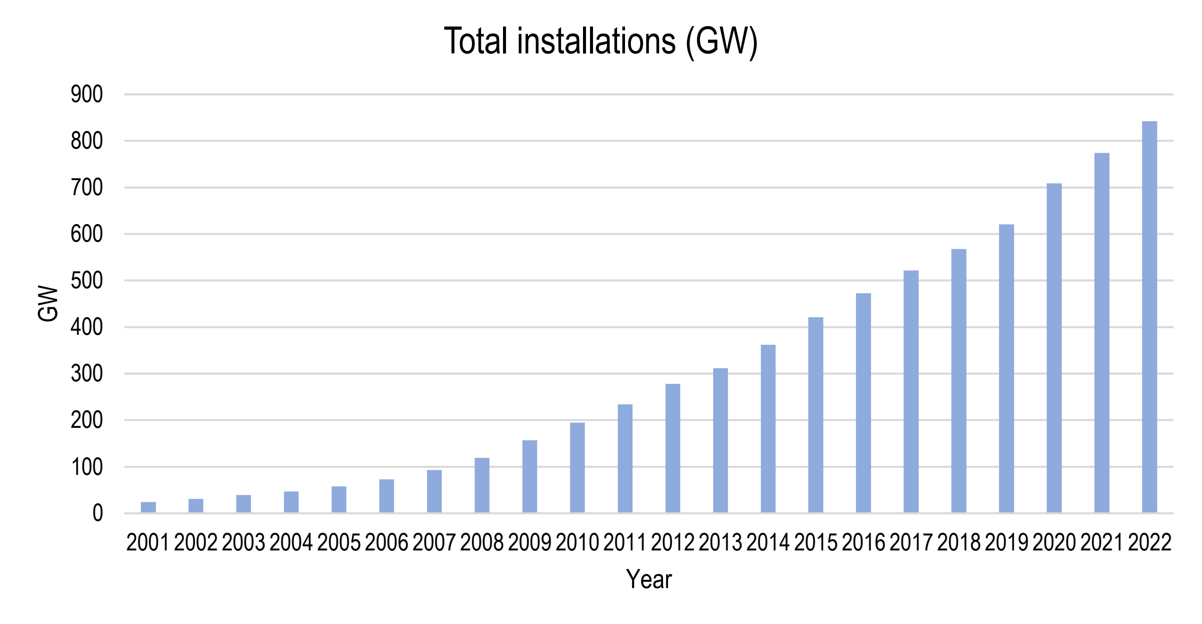

Figure 1: Historic development of wind turbine blades installations onshore, [1] (adapted)

Over time the installed power of the turbines has increased, as well as its size, due to the development of technology associated. Figure 2 presents the blade size evolution per installed power over the years.

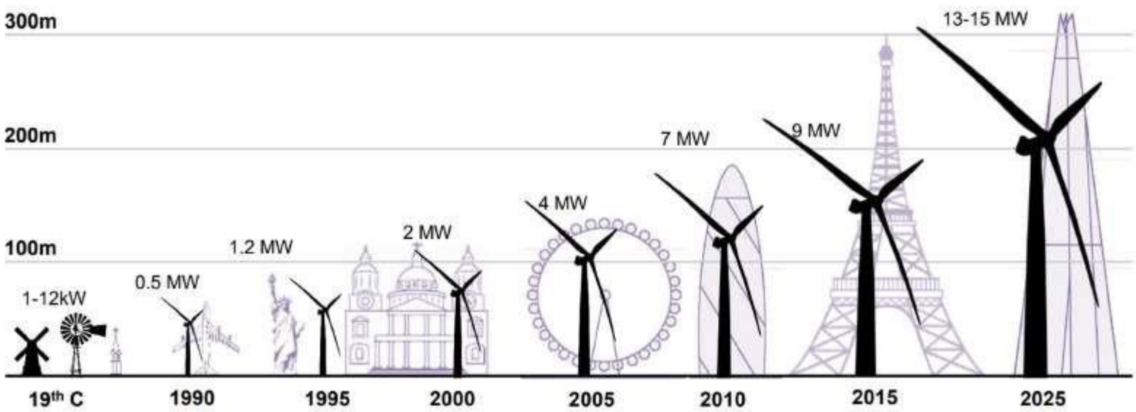

Figure 2: Wind turbine rotor diameter size evolution per installed power, [2]

The wind turbine's lifetime is considered to be 20-25 years [3], and the first wind farms are being decommissioned. From all wind turbine components, about 94% of a wind turbine weight can be recycled, while the other 6%, corresponding the blades, are the problem [3], which arises a concern of what actions should be taken once a wind turbine blades reaches their end of life.

It can be expected more than 375,000 tons of wind turbine blade waste by the year of 2043, only taking into consideration European offshore wind farms [4].

The difficulty regarding the recyclability of wind turbine blades is due to their composition, and will be discussed later in this work.

Given the current dimension of the problem and its projection, the objective of this thesis is a literature review of current recycling technologies for wind turbine blades at their end of life, and comprehend the environmental impact associated with the wind energy.

This thesis is composed of five chapters, divided as follows:

1. **INTRODUCTION**: objectives, explanation of the problematic;
2. **THEORETICAL BACKGROUND AND STATE OF THE ART**: presents the recyclability difficulty associated with the wind turbine blades, as well as the technologies that are being studied and developed to assist on a possible end of life route. Also discusses about the European Waste and Landfill Directives, and how circular economy could take place in this situation;
3. **METHODOLOGY**: materials and methods, databases and criteria used to filter the results for this review;
4. **RESULTS AND DISCUSSION**: analysis of the results obtained from the databases and its considerations;
5. **CONCLUSIONS AND FUTURE WORKS**: what can be concluded from this thesis.

2. THEORETICAL BACKGROUND AND STATE OF THE ART

This chapter will discuss the wind turbine blades and its problematic recyclability, the European Waste and Landfill Directives. Will also mention about the technologies being studied as possible end of life solutions for the blades, and the technology readiness levels of each method. In the end of the chapter, there is a summary of the projects created aiming to study wind turbine blades end of life options, and how the circular economy could take place in this situation.

2.1. Wind Turbine Blades

The blades are made of resin and fibre reinforced polymer, usually glass fiber (GFRP) that, when cured, become cross-linked and undergo an irreversible process, making it difficult to recycle and with no established recycling solutions yet [3]. Carbon fiber is also used, but to a lesser extent, due to its higher costs [5].

Besides the fiber reinforced polymer, the blades also have what is called 'sandwich construction', which consists of multiaxial composite laminates, with balsa wood or polyvinyl chloride (PVC) foam, that are used for the outer shell and for the shear webs in the blades [6].

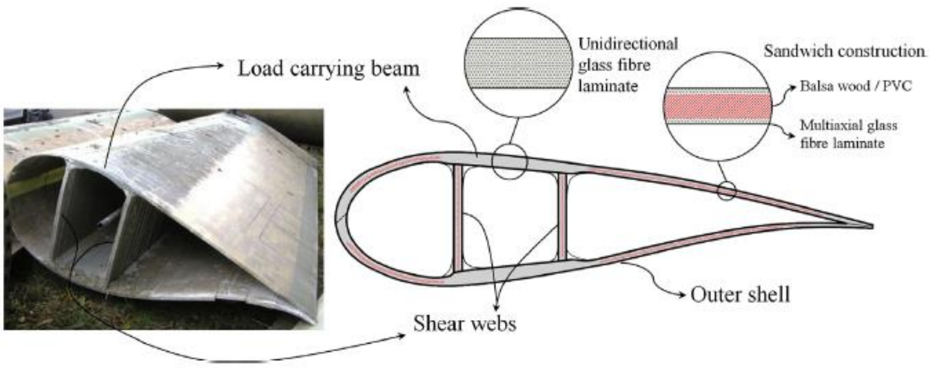

Figure 3: Blade structure, [6]

Another issue regarding the blades composition is that it can have in their composition around 30% of organic material, which shows as risk of being banned from landfill [7]. Some countries, such as Germany, already banned wind turbine blades from being disposed in landfill, due to the total organic content present in the blades [8].

Due to the increasing of weight and length of the blades, and the fact that the first ones are reaching their end of life, there is a big uncertainty of what to do with it next. The situation is getting more problematic each day, since the blades sizes are getting bigger, the first blades are being decommissioned, and no end of life route has been defined for it.

2.2. Legislations

In order to decide and create a route for the waste generated by decommissioned wind turbine blades, some legislations should be taken into consideration.

2.2.1. Waste Directive

The European Parliament and the Council of the European Union set a Directive on waste, Directive 2008/98/EC. This document establishes some measurements for the environment and set some routes for waste.

2.2.1.1. Definitions

Directive 2008/98/EC set some definitions about the subject and treatments.

- **Waste** is defined as any substance or object which the holder discards, intends or is required do discard;
- **Re-use** is defined as "any operation by which products or components that are not waste are used again for the same purpose for which they were conceived";
- **Recovery** means "any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy". Some examples set as recovery operations are using the waste principally as a fuel or other means to generate electricity, which can include incineration facilities dedicated to the processing of municipal solid waste; solvent reclamation/regeneration; recycling/reclamation of organic substances which are not used as solvents, or of other inorganic materials;
- **Recycling** is "any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations";
- **Disposal** is defined by "any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy". Some examples mentioned on the Directive as disposal operations are deposit into or on to land (landfill); incineration on land.

2.2.1.2. Waste hierarchy

The Directive also sets a priority order in waste prevention and management. This is called the Waste Hierarchy, Figure 4.

Figure 4: Waste hierarchy, [9]

This legislation states that when applying the waste hierarchy, measures should be taken to encourage the options that deliver the best overall environmental outcome.

Preventions is defined as “measures taken before a material has become waste, that reduce: the quantity of waste, including through the re-use of products or the extension of the life span of products; the adverse impacts of the generated waste on the environment and human health; or the content of harmful substances in materials and products”.

Preparing for re-use means “checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing”.

Disposal is the last preferrable route and should be avoided.

2.2.1.3. Extended producer responsibility

This legislation also states that measures should be taken to ensure that any natural or legal person, who professionally develops, manufactures, processes, treats, sells or imports products (producer of the product) has extended producer responsibility.

Such measures may include “an acceptance of returned products and of the waste that remains after those products have been used, as well as the subsequent management of the waste and financial responsibility for such activities”.

This would strengthen the prevention and re-use of a product, since the producer would better elaborate the product life-cycle thinking on the overall impacts of the generation and management of such waste.

This legislation also encourages measures regarding the design of products to reduce their environmental impacts and the generation of waste in the course of the production, and subsequent use of products.

Such measures may include “the development, production, and marketing of products that are suitable for multiple use, that are technically durable, and that are, after having become waste, suitable for proper and safe recovery and environmentally compatible disposal”.

2.2.2. Landfill Directive

The European Parliament and the Council of the European Union set a Directive on landfill of waste in 1999 (Directive 1999/31/EC), that was amended in 2020 by Directive (EU) 2018/850.

Those documents set some measure to apply the waste hierarchy and avoid unnecessary use of landfills. Some of those measures is to gradually reduce the landfill of waste. As of 2030, there should be restrictions on landfilling to all waste that is suitable for recycling or energy recovery, unless proven that landfill is the best environmental outcome [10].

2.3. Technologies

Throughout this thesis, articles were researched and investigated. Figure 5 presents the most common technologies considered to be an end-of-life route possibility for the wind turbine blades.

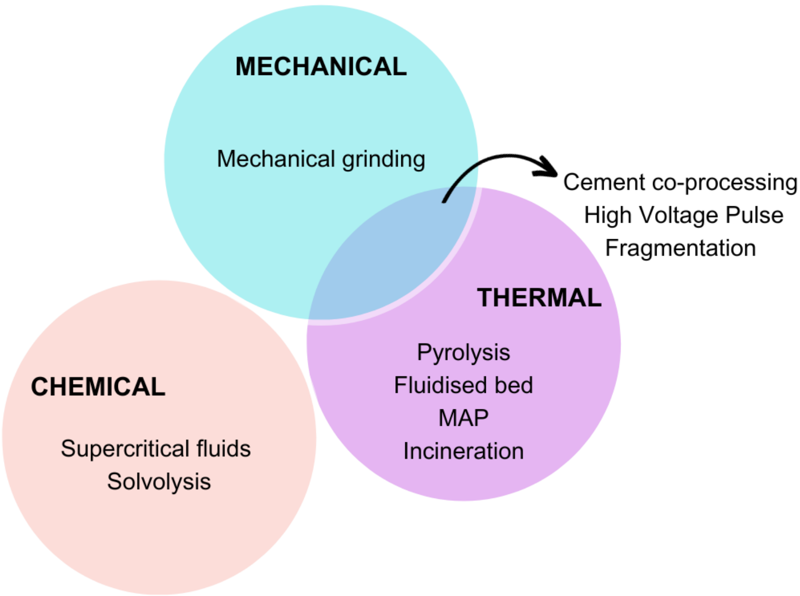

Figure 5: Technologies for recycling wind turbine blades

2.3.1. Mechanical grinding

Also called mechanical recycling, consists of the successive grinding or cutting the dismantled blade into pieces, to reduce the materials to fragments of few millimetres. It is the simplest method, and the only solution that has been brought to a commercial level [6] [11].

This process allows for the use of the material in different ways, such as reinforcement or fillers, and is therefore positioned high on the waste management strategy hierarchy [8] [12].

This method is primarily used on glass fiber recycling, due to the low cost of processing, compared to other methods. Since carbon fiber material is difficult to grind, and the value of this material recycling becomes too low, the mechanical grinding is not viable [12].

2.3.2. Thermal recycling

2.3.2.1. Pyrolysis

Thermal decomposition of the composite that takes place by incineration of the organic polymer binder in a process where the temperature is controlled. During pyrolysis, the polymer breaks down to produce an oil, a gas and a char product, leaving a solid residue. Furthermore, the fibers are reclaimed. Pyrolysis requires high investment and running costs [5] [13] [8].

2.3.2.2. Fluidised bed

Another way to thermally decompose the polymer matrix of composites, and is used to combust the resin matrix and reclaim the reinforcing fibers. This process can treat mixed material, and therefore could be particularly suitable for end-of-life waste [5] [13] [8].

2.3.2.3. MAP (Microwave Assisted Pyrolysis)

Also called microwave pyrolysis, it's a lab-scale recycling technology that involves microwave heating the material from inside, saving energy when compared to conventional pyrolysis. In this method, it is easier to control the heating process, leading to decreased induced damage to the fibre material [11] [14].

2.3.2.4. Incineration

The incineration of the blades for energy recovery has some drawbacks. The glass fibers are non-flammable, toxic gases can be released, and the solid residue from the combustion process needs to be disposed of [15] [16].

2.3.3. Chemical recycling

This technology consists in decomposing the polymer matrix using chemical solvents and then reclaim the fibers [17] [13].

Mishnaevsky (2021) considers this method to be one of the most promising recycling technologies, since it's more clean and obtains higher strength fibers, due to lower temperatures than pyrolysis [18].

2.3.3.1. Supercritical fluids

Also called decomposition method, uses strong solvent properties to decompose the polymers matrices [17].

2.3.3.2. Solvolysis

Chemical treatment where solvents are used to break the matrix bonds at a specific temperature and pressure. Compared to thermal technologies, solvolysis requires lower temperatures to degrade the resins, resulting in a lower damage of the fibres [8].

The recovery projects cover incineration after solvolysis processing, whereas reuse projects describe the use of the recyclate in different applications [12].

2.3.4. Cement co-processing (Cement kiln route)

The co-processing method requires the blade to be shredded (mechanical recycling) and then uses it to substitute fuel and raw materials in the production of clinker. Therefore, co-processing in a cement kiln can be considered both energy recovery and recycling [19].

WindEurope (2020) states that, although it is a very promising method in terms of cost-effectiveness and efficacy, in this process the fiber shape of the glass disappears and therefore cannot be used in other composites applications [8].

2.3.5. High Voltage Pulse Fragmentation

It is an electro-mechanical process that effectively separates matrices from fibres with the use of electricity. The drawback of this method is that only short fibres can be recovered from the process, and to obtain quality fibres requires high levels of energy [8]. This author considers this technology to be a mix between mechanical and thermal recycling.

2.3.6. Mitigate alternatives (environmental impact)

2.3.6.1. Repurpose

Some studies consider repurpose to be a recycling method, since the material is reprocessed into products, and consists of giving a new purpose to the blade. It can also be referred as ‘structural reuse’ (which would be wrong based on the legislation, since the term ‘reuse’ means using the material for the same purpose), or ‘structural recycling’.

Some projects studies using parts of the blade to create for city furniture and playground, office and home furniture, and as a bridge [19].

However, it is unclear how the original design of a composite product affects reuse of structural parts [16].

2.3.6.2. Life extension (LE)

This option consists in extend the lifespan beyond the original design. However, when a product nears its designed end of life, the risk of developing problems increases [11].

2.4. TRL

Technology Readiness Level (TRL) is a measurement system created by NASA, and used to assess the maturity level of a particular technology [20]. This scale was introduced to the European Union funded project in 2012 to determine the development or maturity of a research and its readiness for the market uptake and potential investments [21]. Table 1 shows each TRL and its meaning.

Table 1: TRL stages, adapted from [20]

TRL	Meaning
1	Basic principles observed and reported
2	Technology concept and/or application formulated

TRL	Meaning
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in a space environment
8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
9	Actual system “flight proven” through successful mission operations

Table 2 has a summary of some recycling technologies and their respective TRL according to [8] and [12].

Table 2: Wind turbine blade's recycling technologies and its TRL

Recycling technology	TRL according to [12]	TRL according to [8]
Mechanical grinding GRFP	8	9
Mechanical grinding CRFP	7	6/7
Pyrolysis GFRP	7	9
Pyrolysis CFRP	8	
Microwave heating	3	-
Fluidised bed	4	5/6
Solvolysis	4	5/6
Cement co-processing (cement kiln route)	-	9
High voltage pulse fragmentation	-	6
Incineration	9	-
Landfill	9	-
Microwave Pyrolysis	-	4/5

2.5. Projects

This section shows some of the projects that were with the objective to study and develop possibilities for wind turbine blades at their end of life. Table 3 shows the projects names, their duration and scope.

Table 3: Developed projects and its scope

Project	Duration	Scope	Source
FiberEUse	2017 – 2021	Large scale demonstration of new circular economy value-chains based on the reuse of end-of-use fiber reinforced composites.	[14] [5] [22] [18]
LIFE-BRIO	2014 – 2017	The main objective was to demonstrate an innovative and sustainable methodology for end-of-life wind turbine blades management and recycling from a life cycle perspective.	[14] [5] [23]

Project	Duration	Scope	Source
R3fiber	2018	The project aimed to develop, utilise and commercialise a disruptive technology capable of recovering both glass and carbon fibres from composites in a zero-residue process.	[14] [24]
Selfrag CFRP	2012 – 2014	Implement a high voltage pulse fragmentation process for the recycling of thermoset composite materials.	[14] [25]
EuReComp	2009 – 2012	The objective of the project was to set up a new route to recycle fibre-reinforced thermoset composites via solvolysis.	[14] [5] [26] [22]
GenVind	2012 – 2016	The purpose of GENVIND was to identify and develop new and existing strategies for sustainable recycling of composites, based on cradle-to-cradle philosophies	[14] [5] [27]
Dreamwind	2016 – 2020	The objective was to development new composite materials for future use in wind turbine blades.	[5] [28]
Recycling of Waste Glass Fiber Reinforced Plastic with Microwave Pyrolysis	2011 – 2012	Recycling FRP thermosets via microwave pyrolysis	[5] [29]
REACT	2003 – 2005	Recycling FRP thermosets via mechanical processes	[5] [30]
RECY-COMPOSITE	2016 – 2020	Composite materials recycling. Focus on mechanical and thermochemical recycling of composite materials (pyrolysis and solvolysis) and energy recovery if recycling is not possible.	[22]
MAI Recycling	2012 – 2015	Develop a continuous recycling process chain starting from production rejects or mixed materials through to the processed carbon fiber.	[22] [31]
MAI Recytape	2015 – 2017	Development of a recycling process line for carbon fibres.	[22] [32]
ZEBRA (Zero wastE Blade ReseArch)	2020 – 2023	Consortium between research center and industrial companies with the objective to create an eco-design approach to facilitate recycling, for a 100% recyclable wind turbine blade.	[33] [34] [35]
Blades2Build	2023 – 2025	The project aims to develop solutions for recycling the wind turbine blades.	[36]

Besides those projects, some companies develop their own research and products. A Dutch architectural company, Superuse Studios, designed a playground in 2008 made of decommissioned wind turbine blades in Rotterdam [37] (Figure 6).

Figure 6: Playground in Rotterdam, made from decommissioned wind turbine blades [38]

The same studio also designed a bus stop shelter at Almere Poort's station (Figure 7).

Figure 7: Bus stop shelters at Almere Poort's station [38]

Another example is the Danish company Miljøskærm, that collects discarded fiberglass products such as the ones from wind turbine blades and manufactures insulation products from the recycled material [39].

2.6. Circular Economy

Today’s economy is based on a linear model, where resources are extracted to make products that are used and, after their end of life, are thrown away [40].

The circular economy is a system where materials never become waste and nature is regenerated. It is based on three principles driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature [41].

In a circular economy, the value of products, materials and resources is maintained in the economy for as long as possible, while waste generation is minimised [42].

That said, in 2015 the European Commission adopted its first circular economy action plan, with measures to guide Europe towards a circular economy, production and consumption of waste management and the market for secondary raw materials, besides a revised legislative proposal on waste [43].

In 2020, the European Commission adopted a new circular economy action plan (CEAP), as a part of the European Green Deal, Europe’s agenda for sustainable growth [44].

The Ellen MacArthur Foundation explains that the circular economy has a system diagram, also known as butterfly diagram, that illustrates the continuous flow of materials in this model. There are two main cycles: the technical and the biological one. In the technical cycle, products and materials are kept in circulation through processes such as reuse, repair, remanufacture and recycling. In the biological cycle, the nutrients from biodegradable materials are returned to the Earth to regenerate nature.

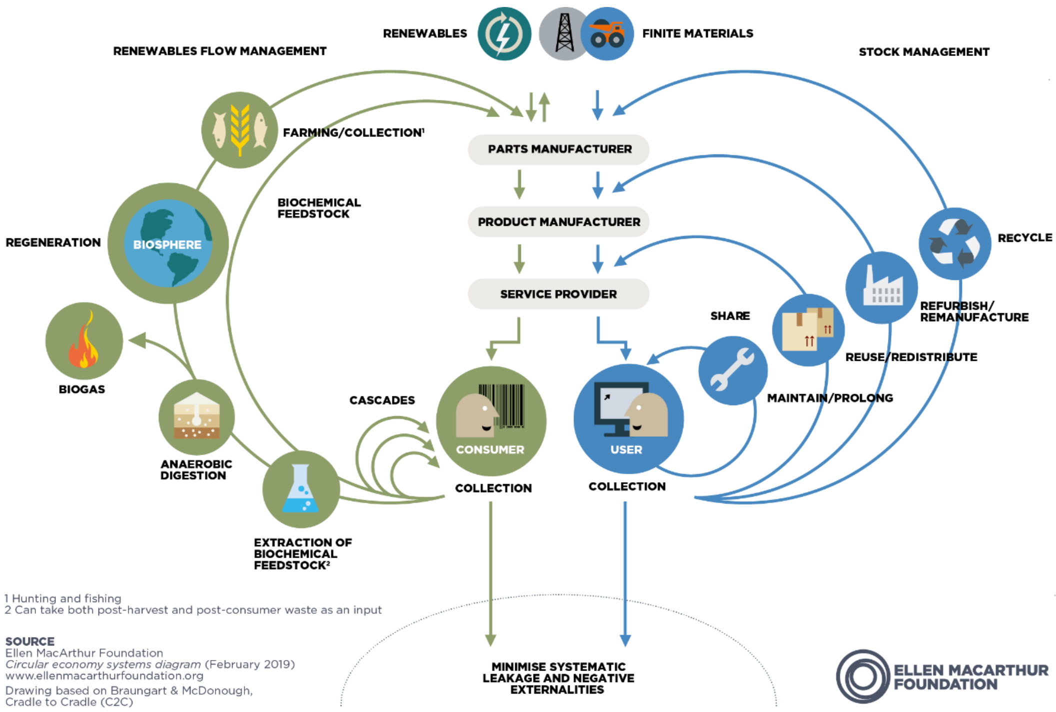

Figure 8: Circular economy diagram. Ellen Macarthur Foundation [41]

Figge [45] defines circular economy as “a multi-level resource use system that stipulates the complete closure of all resource loops. Recycling and other means that optimise the scale and direction of resource flows, contribute to the circular economy as supporting practices and activities. In its conceptual perfect form, all resource loops will be fully closed. In its realistic imperfect form, some use of virgin resources is inevitable”.

In 2019, [46] used the concept of the circular economy to investigate how carbon fibers could re-enter the circular economy system at the highest possible quality, Figure 9.

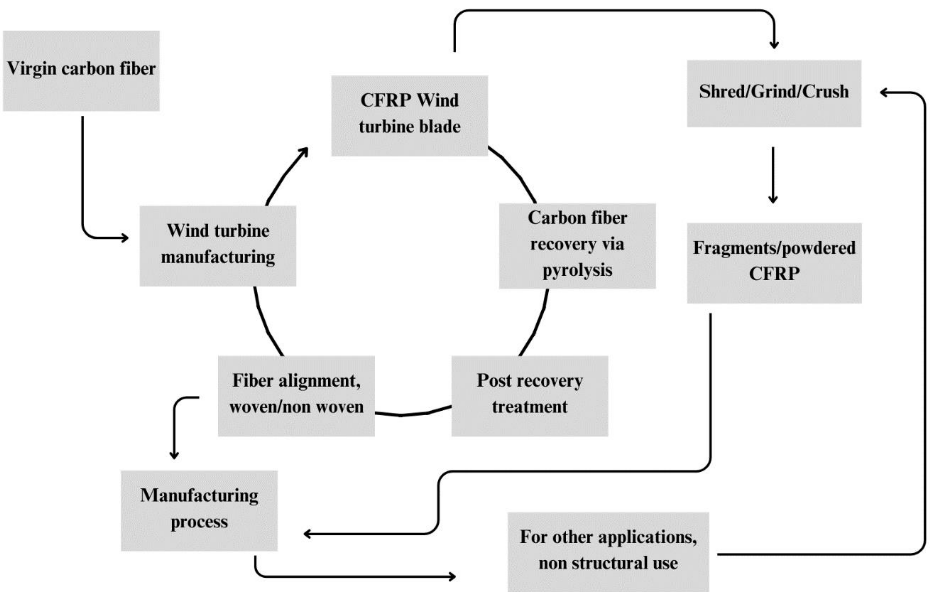

Figure 9: Circular economy applied to carbon fiber, [46] (adapted)

3. METHODOLOGY

This chapter will present the multi-steps process utilised to obtain relevant articles regarding wind turbine blade recycling studies. Figure 10 summarizes the methodology.

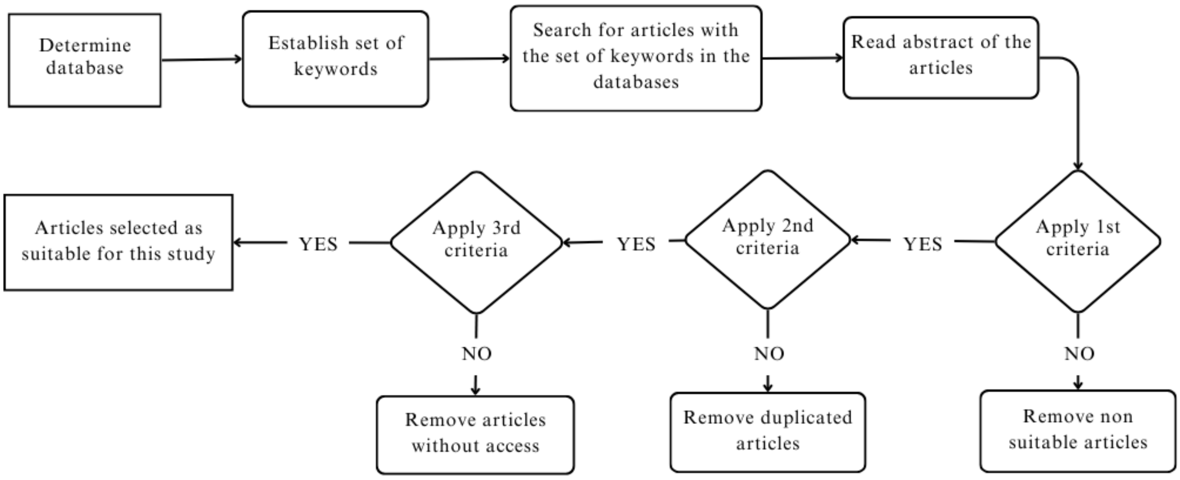

Figure 10: Methodology's flowchart

3.1. Determine database

The review was carried out through published articles available in the two data bases: Scopus (www.scopus.com/) and Web of Science (www.webofscience.com/). Those platforms were chosen based on their reliability on the scientific community and higher content.

3.2. Establish set of keywords

The following keywords were stablished to start the search and filter the results: ‘recycle’, ‘recycling’, ‘landfill’, ‘landfilling’, ‘circular economy’, ‘reverse logistics’, ‘repurpose’, ‘residue’, ‘waste management’, ‘disposal’, ‘reuse’, ‘waste’ and ‘upcycling’. All of those were accompanied by ‘wind turbine blade’.

3.3. Search for articles with the set of keywords in both databases

A total of 26 searches were carried out in each database, between October 12th and October 23rd, 2022.

On Scopus, on ‘Documents’ tab two search fields were added to enter the main keywords of the search, made within “article title, abstract, keywords”, as shown on Figure 11.

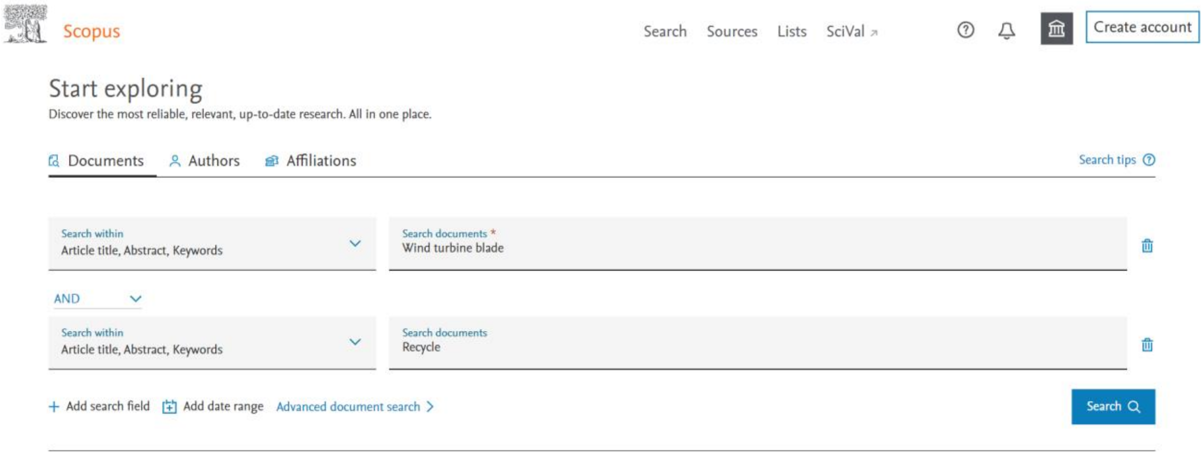

Figure 11: First search done, using the keywords 'wind turbine blade' and 'recycle'

On Web of Science platform, on ‘Documents’ tab, it was also used two search fields and the same set of keywords were entered but, different from the other database. The search was made within “all fields”, since the same option as Scopus was not available.

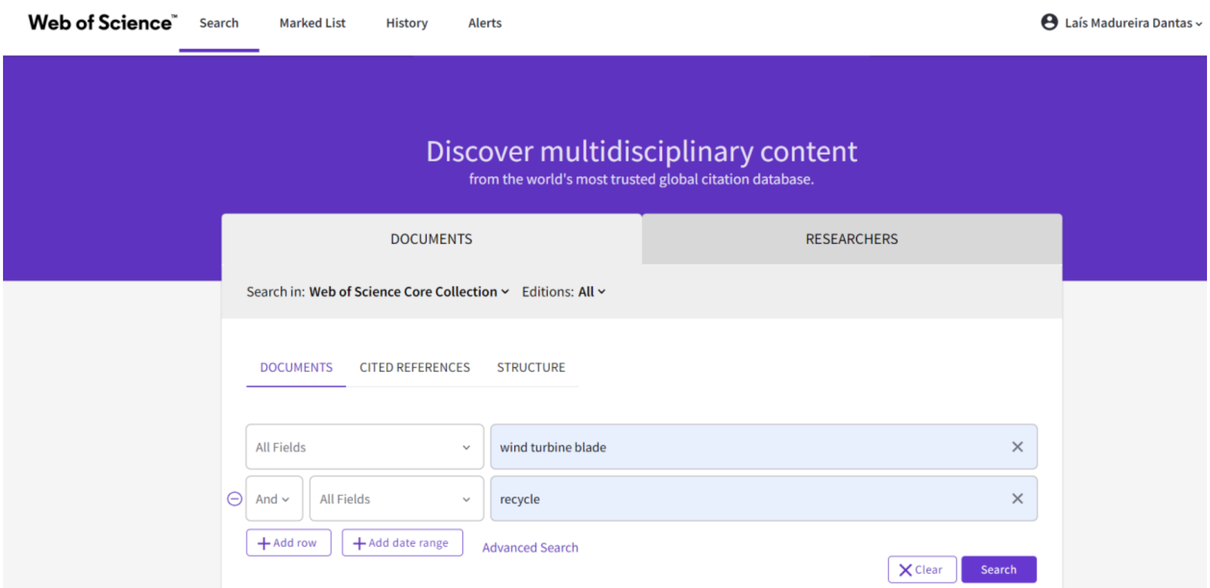

Figure 12: Search made on Web of Science using the keywords 'wind turbine blade' and 'recycle'

3.4. 1st criteria

One of the objectives of this research was to find articles associated with the recycling of wind turbine blade or its components, as well as statistics on the amount of waste being generated from the decommission. Some selection criteria were applied to filter the results.

The first selection criteria was applied by reading the abstract of the articles obtained in the searches. The studies found must address possible destinations for wind turbine blade on their end of life, its recycling (or the recycling of its components) and/or an estimative of waste generation associated with this issue. The excluded cases were those involving changing the composition of the blades, tests on its strength and benefits, and comparisons between materials to change the currently used material.

3.5. 2nd criteria

Given that the some set of keywords were similar and the same sets of keywords were used in two different databases, some duplicated results were obtained. The second selection criterion was to ignore the duplicates.

3.6. 3rd criteria

The third criterion was based on the article's availability, whether it had free access or if the author had access through their associated institutions, the Polytechnic Institute of Bragança (IPB) and University of A Coruña (UDC). Although some studies had abstracts that approached the desired topic, paid articles or the ones that the universities didn't had access to were discarded.

Table 4 shows the number results obtained and the total number of articles selected after all criteria were applied.

Table 4: Results obtained from the searches and total number of articles selected after criteria were applied

Keywords	**Database**		**Total results**	**Selected articles**
	Scopus	**Web of Science**		
Wind turbine blade + Recycle	17	82	99	19
Wind turbine blade + Recycling	108	87	195	41
Wind turbine blade + Landfill	15	17	32	3
Wind turbine blade + Landfilling	4	17	21	0
Wind turbine blade + Circular Economy	18	18	36	2
Wind turbine blade + Reverse Logistics	3	1	4	0
Wind turbine blade + Repurpose	1	3	4	0
Wind turbine blade + Residue	16	12	28	1
Wind turbine blade + Waste Management	33	25	58	1
Wind turbine blade + Disposal	37	26	63	1

Keywords	**Database**		**Total results**	**Selected articles**
	Scopus	**Web of Science**		
Wind turbine blade + Reuse	36	41	77	0
Wind turbine blade + Waste	133	99	232	1
Wind turbine blade + Upcycling	0	0	0	0
Total	421	428	849	69

After that, the selected articles were read, and its impressions and observations are presented on Chapter 4.

4. RESULTS AND DISCUSSION

In this section the results obtained from the searches are presented.

From the 69 articles selected, there are authors representing institutions from different countries, and some articles have authors from one or more countries, meaning that out of 69 articles, there are 91 locations. From those, approximately 59% of the authors represent institutions located in Europe, followed by the ones from North America, 23% (Figure 13).

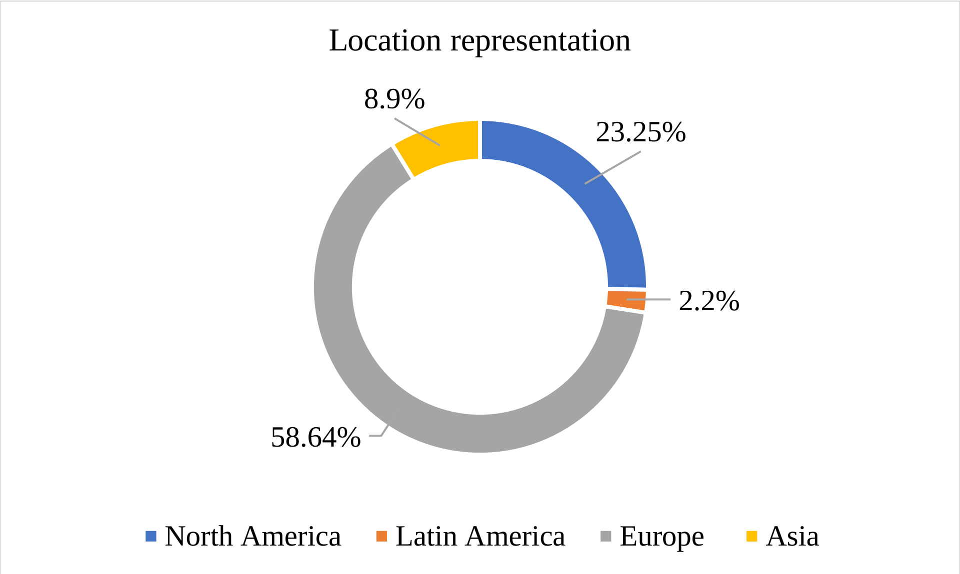

Figure 13: Location's representation of the selected articles

The Latin America articles and authors were published only in Brazil, and the North America ones corresponds the United States of America, followed by Canada.

The articles from Asia are from the following countries: China, India, Malaysia, Kazakhstan and Russia (Figure 14).

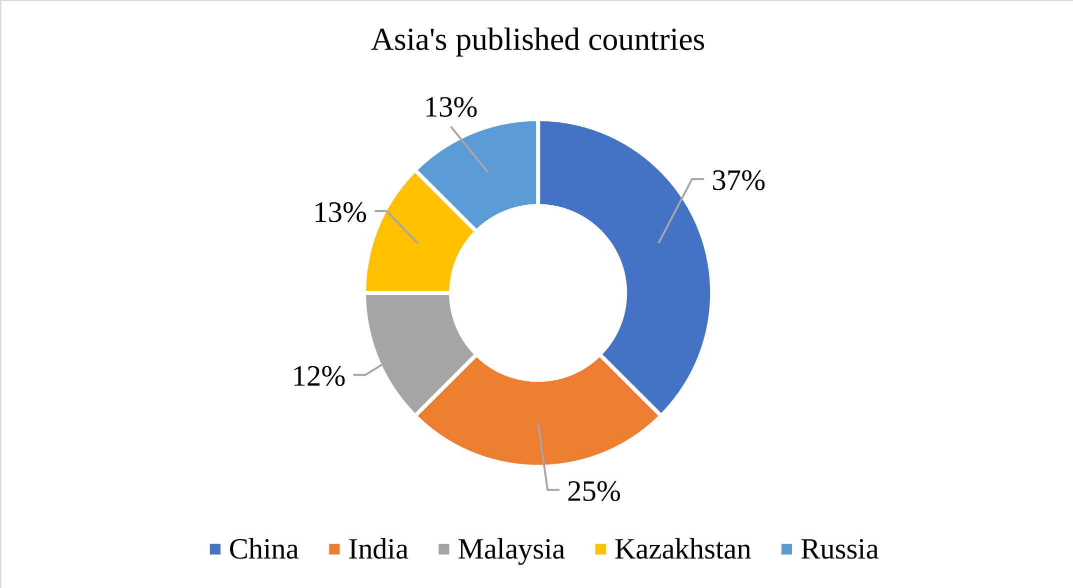

Figure 14: Asia's published countries

The region with most studies and authors published is Europe, having the United Kingdom the country with more authors published, followed by Denmark, as it is possible to see on Figure 15.

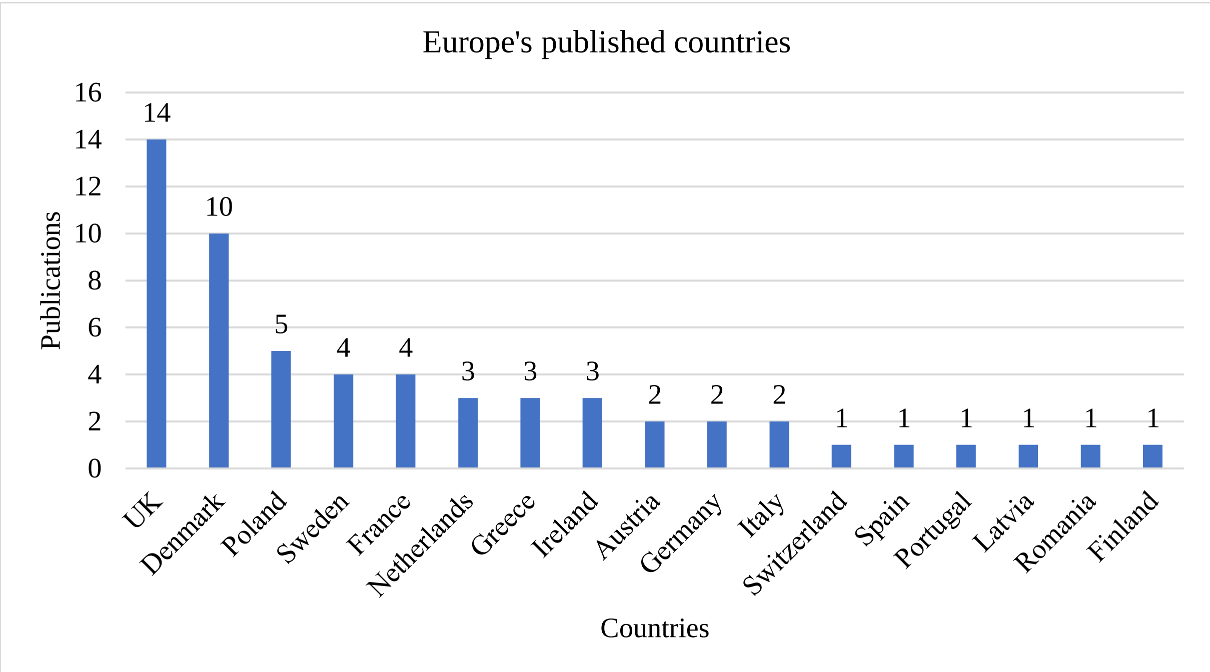

Figure 15: Europe's published countries

Another important topic is that, while analysing the articles, one noticed that some references were cited several times: ‘Recycling of wind turbine rotor blades – fact or fiction?’ [47] and ‘Recycling Wind’ [48]. Therefore, a further investigation was done to find out how often it was repeated.

During that persue, one noticed one more thing: the ‘Recycling Wind’ author, Larsen, was cited for this work or ‘Recycling wind turbine blades’ [49]. Both articles are very similar, but just the first one was obtained as a search result.

Albers was one of the first authors to publish an article on this issue regarding the wind turbine blades’ end of life, followed by Larsen, who cites Albers. Both works were published in 2009.

As a result of this particular investigation from the 69 selected articles, 12 mentions Albers, 25 mentions Larsen. Therefore, 37 articles cite the first works on the subject, representing around 53.62% of the studies selected for this work. From those 37 articles, 7 cites both of the works.

The extensive Table 5 contains the articles obtained as a result from the searches and some synthesis.

Table 5: Articles obtained from the searches and considerations

Article	Year of publication	Synthesis	Cites [47]	Cites [48]	Cites [49]
[17]	2021	• Aims to find out the optimum recycling process from existing recycling methods to recycle end of life wind turbine blade waste • Concludes that microwave assisted chemical recycling is a green, energy-efficient, and most sustainable recycling method • Uses the term 'reuse' as 'recycling'	Yes	No	Yes
[50]	2021	• Provide an estimation of the mass and volume of wind turbine blade waste in each United States state by 2050 and compares to the estimated landfill capacity until then • Suggests to reexamine the blade design by considering new materials • Concludes that the total amount of blade waste in the United States comprise 1% of landfill capacity by volume and 0.02% by mass • With the results found in this study and the costs of disposing wind turbine blades in landfill makes it unlikely to motivate a shift to circular economy for those composite under current policy conditions in the USA	No	No	No
[15]	2020	• Estimates the wind turbine blade waste material for Europe until 2050, distinguishing between offshore and onshore • Concludes that onshore wind turbines will constitute the greatest part of the total installed capacity and waste amount. Also mentions that this situation should be considered for designing any circular economy, recycling or disposal system for this type of waste	Yes	No	No
[51]	2019	• Investigates the use of fiber glass scrap from wind turbine blades as reinforcement in thermoplastic filaments for 3D printing to improve mechanical properties of 3D printed thermoplastic parts without the need of adding high cost virgin fibers • The study describes and validates a methodology integrating mechanical recycling and fused filament fabrication 3D printing as a potential solution to the problem of composite waste from wind turbine blades	Yes	No	Yes
[52]	2019	• Objective is to quantify all wind turbine wastes and flows across the Champagne-Ardenne (CA) region from 2002 to 2020, taking into account end of life issues	No	No	No

Article	**Year of publication**	**Synthesis**	**Cites** [47]	**Cites** [48]	**Cites** [49]
[53]	2019	• Evaluate the amount of CFRP waste generated by end-of-life wind turbines through 2050 • States that we have approximately 22 years (from 2019) to establish a recycling system for CFRP working at an industrial scale • States that pyrolysis technology is the only recycling approach that allows to recover carbon fibres at an industrial scale	No	Yes	No
[54]	2019	• Focuses on different fiber reinforced plastics (FRP) waste recycling methods and their comparison by carrying out literature review and using multi-criteria decision making analysis • States that chemical recycling is the method that shows best results in terms of recovered material quality, and it is nor used on an industrial scale • Mentions that the lack of demand for recycled reinforcement fiber is a restricting factor for implementing global industrial scale recycling system • Concludes that more studies about polymer matrix composite waste recycling methods need to be carried out	No	No	No
[5]	2018	• Presents the state of the art in how industry is addressing the challenges associated with composite waste and the ways in which composite waste from wind turbine blades can be managed according to the best available technologies • Mentions recycling methods as recovery, and only considers as recycling the mechanical one • Mentions about circular economy in the wind turbine blade recycling scenario • Concludes that need to be proved that there is market for glass fiber reinforced polymers secondary applications, and improvements need to be done	No	Yes	No
[55]	2018	• Uses "repurposing or recycling" as if it were different things. By definition, is the same • Investigates some second generation composites fabricated using wind turbine material and a polyurethane adhesive • "It is feasible to recycle the wind turbine blade to fabricate value-added high-performance composite." • Concludes that recycled wind turbine blade is a viable material for making second generation composites	No	No	Yes

Article	**Year of publication**	**Synthesis**	**Cites** [47]	**Cites** [48]	**Cites** [49]
[7]	2012	• Considers the producer responsibility scenarios for manufacturers to recycle wind turbine blades, and investigates the current and future methods of its disposal • States that end of life options for composite wind turbine blades is an increasing issue and landfilling it is becoming unacceptable • Also states that manufacturers need to take the first steps to develop wind turbine blade designs for recycling • Mentions about the importance of the legislation in this situation	No	No	Yes
[48]	2009	• Published in 2009, shows some possible routes for wind turbine blades at their end of life • Mentions about new ways of producing wind turbine blades in order to facilitate the disposal and recycling process	Yes	No	No
[56]	2021	• Examines the viability of valorizing waste glass fiber reinforced polymer materials extracted from wind turbine blades into concrete • Concludes that, with the removal of the wooden content, the glass fiber is a promising material for valorization in concrete construction	No	No	No
[57]	2021	• Predicts the future wind turbine blade waste in Canada and the end of life options • States that cement kiln coprocessing achieves net zero emission by converting waste into energy and raw materials for the cement. Mechanical recycling can achieve substantial reductions in primary energy demand and greenhouse gas emissions but achieving financial viability would likely require substantial regulatory support	No	No	No
[58]	2021	• Estimates the regional waste generation from rotos blades from the Germany wind turbine stock between 2020 and 2040 • States that cement industry is the only demander of GFRP from rotor blades for thermal recovery	Yes	No	Yes

Article	**Year of publication**	**Synthesis**	**Cites** [47]	**Cites** [48]	**Cites** [49]
[59]	2021	• Studies the effect of incorporating recycled fiberglass, reclaimed from wind turbine blades, on tensile properties of 3D printed specimens by filament fabrication • Shows that recycled fibers exhibited higher strength and stiffness values compared to virgin fibers, which indicated that using recycled fiberglass is a competitor to fused filament fabrication 3D printing feedstock reinforced by virgin fiber glass • Mentions that mechanical recycling is considered to be the only mature and environmentally friendly process found in the current market	No	No	Yes
[60]	2021	• Compares the sustainability of ways to deal with wind turbine blade waste, between landfill, incineration with heat recovery, co-processing in cement kilns, furniture and bridge fabrication, using the UN Sustainable Development Goals (SGDs) • Concludes that bridge fabrication is the most sustainable alternative, followed by furniture making	No	No	No
[61]	2021	• Reviews the current recycling methods for wind turbine blade end of life and the current TRL for those technologies • Concludes that recycling through co-processing in the cement industry is the most applicable, environmentally friendly and economically appropriate recycling method that can handle large amounts of waste materials from the wind turbine blades	Yes	No	No
[62]	2021	• Introduces a spatiotemporal approach to investigate the magnitude of the problem and quantify blade waste material in Ireland • States that Irish wind industry will face a challenge due to the potentially large volumes of blade waste material	Yes	No	Yes

Article	Year of publication	Synthesis	Cites [47]	Cites [48]	Cites [49]
[63]	2021	• Focus on the identification of an upper and lower economic value of glass fibre from wind turbine blades recycling • States that all recycling processes show a negative effect on mechanical properties • States that the European Union should promote altering the policies by introducing strategies for recycling behaviour • Concludes that numerous markets are available for wind turbine blades recycled material, primarily for grinded products, followed by pyrolysed glass fiber	No	No	Yes
[64]	2021	• Investigates the scale of material stocks and flows regarding wind power development in Guangdong from 1989 to 2050 • States that dismantling and recycling strategies based on local realities need to be introduced to ensure that relevant disposal capacity is properly planned in advance and the waste will be handled in a timely and appropriate manner • Mentions that recycling waste blades instead of landfill and incineration is the most effective way to improve the sustainability of the wind power sector	No	No	Yes
[65]	2021	• Presents a step-by-step recycling solution to manufacture fiber reinforced filaments for fused filament fabrication • Mentions that the recycled fused filament fabrication exhibited superior tensile properties compared with the pure polymer one	No	Yes	No
[66]	2021	• Reviews the state of the art of composite wind turbine blades recycling, analyzing the most important methods • States that mechanical recycling is the most economically feasible and mature technology, but that new markets for mechanically recycled composites need to be created	No	No	No
[16]	2021	• Investigates the effect of the original product design on the recycling and use composite products, taking wind turbine blades as case material • Uses ‘reuse’ as ‘recycling’ • Were able to take wind turbine blades and use it to a next product lifecycle, a picnic table	No	No	No

Article	Year of publication	Synthesis	Cites [47]	Cites [48]	Cites [49]
[18]	2021	• Reviews the various approaches and strategies of end-of-life management of wind turbine blades, from landfilling and incineration, via life extension, reuse and recycling, to the development of new smart, bio-based and biodegradable materials • Uses 'reuse' as 'recycling' • Concludes that, in view on the sustainability of technologies, the repair, reuse and refurbishment technologies show some advantages, as compared with recycling	No	Yes	No
[67]	2021	• Shows a prediction analysis on the design of future cost-minimal recycling and recovery of GFRP and CFRP from rotor blades of wind power plants based on a mathematical optimization model • States that co-processing in cement kilns is the most preferred treatment for glass fiber reinforced polymer recycling • Mentions that chemical recycling for glass fiber reinforced polymer is unlikely due to high costs and low quality of recycled	No	No	No
[68]	2021	• Investigates the feasibility of the circular economy pathway of mechanical recycling for use of end-of-life blades at composite material manufacturing, and aims to identify the optimal reverse supply chain network design for end of life wind turbine blades • Concludes that even with the optimal supply network the breakeven price required for the recycled material is marginally competitive to the currently used virgin filler materials for scenarios in 2050	No	No	Yes
[69]	2020	• Synthesizes and extends identified design for recycling principles based on a review of published industrial and academic best practices • Suggests that a favorable option for the blades would be changing its material • States that designing wind turbine blades that materials maintain value after recycling is a key research need • States that successful application of design for recycling principles offers potential for environmental and economic benefits to manufacturers and end users	No	No	No

Article	Year of publication	Synthesis	**Cites** [47]	**Cites** [48]	**Cites** [49]
[70]	2020	• Investigates a common wind turbine blade life cycle assessment and compares it to a hypothetical blade where a recyclable resin system is used • States that efforts should be invested in research and innovation to diversify and scale-up composite recycling technologies, to develop new, high-performance materials with recycling abilities • Mentions that existing treatment routes like cement co-processing must be deployed more widely to deal with the current waste streams	No	No	No
[71]	2020	• Investigates the possibility to develop a general solvolysis process that can accept all materials constituents in a wind turbine blade • Concludes that solvolysis have the possibility to act s a recycling method of cleaning GFRP from wind turbine blades before further processing and upgrading in a refinery, but requires continued method development in order to reduce the consumption of energy and chemicals	No	No	No
[72]	2020	• Uses 're-use' as 'recycling', since they mention the use of a wind turbine blade for bridges • States that "Reuse means to either extend the products lifetime, or to reuse it in a new product by taking advantage of its original design purpose." • The main objective was to investigate the possibility of a pedestrian bridge made of decommissioned wind turbine blade • Considers that building bridges out of decommissioned wind turbine blades is a promising solution	No	No	No

Article	**Year of publication**	**Synthesis**	**Cites** [47]	**Cites** [48]	**Cites** [49]
[73]	2020	• Uses the terms with the correct definitions, although treats 'Repurpose' not as a way of recycling • Discusses about some existing composite recycling technologies and its limitations • Uses a different waste hierarchy pyramid • The paper develops a composite recycling scenario that allows using the composite material properties and scalability at the same time by using Industry 4.0 and digital fabrication. It suggests to investigate the specific value creation in composite recycling and to create a proof of concept in order to verify the theory developed in the work • Considers that the existing composite recycling technologies aren't viable due to high costs, low value applications and diminished mechanical properties	No	No	No
[74]	2020	• Investigates the potential of a treatment to increase the strength of glass fiber thermally recycled from wind turbine blade • States that substantial improvements in recycled glass fiber strengh and fiber-polymer adhesion can be achieved after using the regeneration treatments shown in the study, producing recycled glass fibres with significantly enhanced reinforcement potential	No	No	No
[75]	2019	• Investigates using recycled wind turbine blade as a feedstock of second-generation composite • Evaluates an economically viable composite fabrication system using mechanically recycled wind turbine blade material as a feedstock for thermoplastic composites • Shows some cases which favor the use of recycled wind turbine blade material as the reinforcement in extruded composites	No	No	No
[76]	2019	• The research experimentally examine the effect of the recycled fibers extracted from rotor blades wastes on the tensile properties of 3D printing fused filament fabrication specimens • States that the material can be effective in enhancing the structural stiffness of fused filament fabrication 3D printed components	Yes	No	Yes

Article	**Year of publication**	**Synthesis**	**Cites** [47]	**Cites** [48]	**Cites** [49]
[77]	2019	• Analyses different classes of wastes and its possible recycling • Mentions that since the wastes are very complex and heterogeneous materials, containing different impurities that can represent serious obstacles toward their reuse/recycling	No	No	No
[78]	2019	• Dataset of the physical properties regarding article "Extruded composites from wind turbine blade material" [75]	No	No	No
[79]	2019	• Gives an overview of the main recycling technologies and applications of recycled products • Uses the term ‘reuse’ as using again, which can be confusing talking about the definitions on the directive • Mentions that new environmental friendly blade materials should be designed from the source • States that is necessary to optimize the recycling methods to make it more cost-effective, less or even pollution free and more efficient. Mentions that recycled fiber has no competitive advantage in performance and has limitation on the application field	No	No	No
[80]	2019	• Shows the perspectives of the wind energy under the triple bottom line of sustainability • Focuses on the impacts of the wind energy in human activities and environment • Does not address issues related to the end of life of wind turbines	No	No	No
[11]	2019	• Analyses and compares end-of-life options for wind turbine blade materials in terms of environmental impact focusing on energy consumption • Mentions that there is considerable variability in the results and lack of consensus on predictions for the future • States that the most environmentally favourable process is dependent on the blade's material, and concludes that for hybrid blades or glass fiber ones, the mechanical recycling is the best option at this moment, while for carbon fiber blades, the best option is fluidised bed	No	No	Yes

Article	**Year of publication**	**Synthesis**	**Cites** [47]	**Cites** [48]	**Cites** [49]
[81]	2019	• Investigates the feasibility of recycling composite wind turbine blade components that are fabricated with glass fiber reinforced Elium® thermoplastic resin • Concludes that recycling thermoplastic glass fiber composites via solvolysis is commercially feasible under certain conditions • Also mentions that pyrolysis show that relatively little energy is required to decompose the polymer matrix from composites when compared to other recovery techniques; however, the loss of the high-embedded-energy polymer is a disadvantage of this recovery option	No	No	Yes
[82]	2019	• Uses 'reuse' when it should be 'recycle' • Focuses on emphasizing the necessity of creating markets for recycling composites • States that is necessary to research the means of improving the wind turbine blade manufacturing process • Concludes that recycling composite materials on an industrial scale is a very difficult task, underpinned by the few techniques available • "Advancement of technologies that allow reuse or recycle of, as the case is, high-value materials"	No	No	No
[13]	2019	• Presents some end of life treatment methods for carbon fiber reinforced polymer • Concludes that the optimal technology is pyrolysis, which leaves the quality of the recycled fibres somewhat degraded whereas mechanically recovered fibres present problems in the interface and result to inadequate binding with a new matrix	No	No	No
[83]	2019	• Investigates the possibility of using glass fibres obtained in pyrolytic recycling of disused wind turbine components as a poly(vinyl chloride) filler • States that is possible to obtain PVC composites with glass fibres with a carbon deposit, which are formed during the pyrolytic recycling • Also mentions that the increase in percentage of fibres used in PVC causes an increase in the modulus of elasticity of the obtained composites while reducing the value of tensile and impact strength	No	No	No

Article	Year of publication	Synthesis	**Cites** [47]	**Cites** [48]	**Cites** [49]
[84]	2018	• Shares an analysis of current and potential decommissioning scenarios for end of life composite wind blades • States that planning for end of life composite blades involves several layers of management, and that the major barriers to wind blade end of life include a combination of parameters from the material itself to the economical scale-up of composites' recycling	Yes	No	Yes
[85]	2018	• Uses 'reuse' as 'recycling'. The title of the article should be 'Concepts for recycled composite materials from decommissioned wind turbine blades in affordable housing' • The paper shows conceptual architectural and structural options for recycling wind turbine blades by using parts of it in housing projects • The blade used in this simulation wasn't manufactured • It shows that it's possible to use parts of a blade in housing projects, but the paper mentions that further investigation should be done regarding structural analysis, logistics, cost, social accessibility and others	Yes	No	No
[86]	2018	• Investigates testing and assessment procedure for destructiveness of the life cycle of wind power rotor blades	No	No	No
[87]	2018	• Mechanically processed a wind turbine blade shell to get slender elements, called 'Needles', and mixture into concrete in order to investigate the properties of the material • Shows that the 'Needles' increased the toughness (energy absorption capacity) of concrete significantly	No	No	No

Article	**Year of publication**	**Synthesis**	**Cites** [47]	**Cites** [48]	**Cites** [49]
[88]	2017	• Investigates the main economic and environmental issues with various wind turbine disposal methods • Considers recycling methods, such as mechanical, thermal and chemical as disposal methods • States that the best option is to move toward a different, more sustainable manufacturing process in material and design that also allows optimal disposal • Mentions that, by the time the article was published, the cheapest option of disposal in the USA was landfilling wind turbine blades, despiting the negative consequences and that it is the least preferred method on their waste management hierarchy • States that none of the current methods allow optimal wind turbine blade disposal	No	Yes	No
[89]	2016	• Develops a method to predict the future waste related with the wind turbines in Sweden • States that a development of an industry is important to be able to handle end of life wind turbine blades materials in a sustainable way, and that switching to a more easily recyclable material could be part of a long term solution	No	No	No
[6]	2016	• The main objective is to characterize mechanical properties of polyester resin composites reinforced with shredded composites, and to assess the potential of such recycling solution • Concludes stress-strain curves revealed composite failure at unusual low strain values, and micrographs of the fracture surface indicated poor adhesion between the shredded composite and matrix. States that, to tackle this problem, chemical treatment of shredded composite or use of an alternative resin, to improve bonding should be investigated	No	No	Yes

Article	**Year of publication**	**Synthesis**	**Cites** [47]	**Cites** [48]	**Cites** [49]
[90]	2014	• Summarizes the literature on using solid residue recovered from glass fiber reinforced polymer from wind turbine blades, like shredded composites or glass fiber, as reinforcement in new polymer composite • States that all studies should be conducted in a normalized manner to allow comparison between all results • Concludes that replacing virgin fibres by shredded composites or recovered glass fiber in new polymer composites generally decreases the flexural and tensile properties of the composite, when compared to a composite only made by virgin fibres	Yes	No	No
[91]	2012	• Investigates the possibility of recycling glass fibre reinforced composites by microwave pyrolysis • Concludes that the tests showed the recycled glass fibre had relatively low mechanical properties, and that a good use of those fibres could be as a reinforcement for thermoplastic resins	No	No	No
[19]	2020	• Aims to determine the most sustainable disposal method for Irish blade waste comparing three scenarios: Co-processing in cement kilns in Germany, co-processing in Ireland, and landfill in Ireland • Concludes that co-processing of Irish blade waste at a 10% material substitution rate in a German cement kiln was found to be six times better environmentally than depositing waste in an Irish landfill • States that further research is needed to establish the costs of coprocessing in Ireland as compared to suggested repurposing solutions. Also mentions that policy changes are needed that would require wind farm owners to post a decommissioning bond upon build completion, to cover the costs of sustainable disposal methods. • Gives a suggestion that tax allowances and penalties may also be used to reward the utilization of solutions that are higher on the waste hierarchy. • States that a directive similar to the End of Life Vehicle directive (European Parliament, 2000) should be put in place	No	No	Yes

Article	Year of publication	Synthesis	**Cites** [47]	**Cites** [48]	**Cites** [49]
[92]	2017	• Studies the possibility of using glass fiber waste, provided from wind turbine blades, as a reinforcement agent in inorganic polymers • States that it's possible and viable to use the material as a reinforcement agent, reducing geopolymer production costs and mitigating the waste's environmental impact	No	No	No
[93]	2016	• The study aims to provide a quantitative assessment of the lifetime environmental impact of wind turbine blades • Concludes that CFRP blade energy consumption is around 50% higher than GFRP	No	No	No
[94]	2021	• Uses 'reuse' as 'recycling' • Investigates the structural recycling of a particular wind turbine blades as furniture, creating a picnic table made from blade segments • States that further research can be done in order to expand on additional products and design use	No	No	No
[95]	2020	• Uses 'reuse' when it should be 'recycle' • It evaluates the user safety of the playground built from decommissioned wind turbine blades, Wikado, and if it is safe to use this material for a playground purpose • States that in Wikado the embodied energy and use of natural resources was lower, compared to a standard playground • It is possible to conclude that is viable to recycle wind turbine blade into playgrounds as far as maintenance and inspections are done regularly	No	No	No
[96]	2020	• Aims to carry out an ecological, technical and energetical transformation analysis of selected postproduction waste of wind power plants based on life cycle assessment models and methods • Concludes that the use of recycling processes can reduce the level of negative impact over the entire life cycle of all types of waste of wind power plant blades	No	No	No

Article	**Year of publication**	**Synthesis**	**Cites** [47]	**Cites** [48]	**Cites** [49]
[97]	2017	• Aims to discover the magnitude of the wind turbine blade waste problem • Concludes that Europe will be the first one to face the issue with wind turbine blades waste, and ultimately China will have the largest waste inventory. Mentions that end-of-life options for decommissioning wind turbine blades need to be explored with the aim of providing environmentally favourable guidelines for managing wind turbine blade waste	Yes	No	Yes
[98]	2020	• Evaluates an environmentally beneficial use for the wind turbine blade waste by incorporating it in cement-based mortars • States that the incorporation of wind turbine blade waste in cementitious matrices offers advantages from both economic and environmental perspectives	No	No	No
[99]	2019	• Dataset of the mechanical and thermal properties regarding article "Extruded composites from wind turbine blade material" [75]	No	No	No
[100]	2021	• Uses the conception of circular economy to analyse the most important methods of material recovery form multilateral composites, including wind turbine blades • Mentions about a recycling method not mentioned in any other one that one read, mixed methods using microorganisms for degradation composites. Informs that the usage is limited even at laboratory scale • Uses 'reuse' as 'recycle' • States that is required to develop new technologies and improve the existing ones, and that proper law regulations are needed • Concludes that composite materials in a circular economy is a challenge, since its recycling still an immature area. Mentions that a new solution dedicated to new products is needed	No	No	Yes
[101]	2018	• Dataset of the physical properties of material made on article "Recycled wind turbine blades as a feedstock for second generation composites" [55]	No	No	No
[102]	2018	• Dataset of the mechanical properties and internal bond of material made on article "Recycled wind turbine blades as a feedstock for second generation composites" [55]	No	No	No

Article	Year of publication	Synthesis	**Cites** [47]	**Cites** [48]	**Cites** [49]
[103]	2020	• Investigates the tensile properties of recycled glass fibers from scrap wind turbine blades, through thermal and mechanical methods, and their interface strength with polylactic acid (PLA) • States that the recycled fibers through thermal process shows significant reduction of the tensile strength when compared to the one that were mechanically recycled	No	No	Yes
[104]	2020	• Examines recent literature data on life cycle assessments of various technologies for recycling of wind turbine blades and photovoltaic panels • States that technologies for recycling wind turbine blades need further development • Mentions that the economic characteristics of various recycling processes are absent in the literature because the methods are still at laboratory stage	No	No	No
[105]	2021	• Investigates an integration of a sustainable circular economy into the design, development, operation, and end of life management of offshore wind infrastructure • States that the proposed circular economy framework can increase the sustainability of the management of offshore wind infrastructure	No	No	No
[106]	2021	• Investigates about using recycled glass fiber reinforced polymer as a replace of sand in mortar • Concludes that recycled glass fiber reinforced polymer showed promising results as partial replacement of sand in mortar	No	No	No
[107]	2018	• The main focus of the study was to investigate a way to improve the carbon sequestration from sewage sludge. The wind turbine blade waste was used to perform a co-pyrolysis system of sludge • Concludes that the co-pyrolysis od wind turbine blade waste and sewage sludge will be a promising way to improve the carbon sequestration from sewage sludge, when introducing the right ratio of wind turbine blade waste	No	No	Yes

From the synthesis presented on Table 5 it is possible to note that, although the Waste Directive was implemented in 2008, 13 articles use the wrong definitions of the terms. The most common misuse is regarding the term ‘reuse’ when it should be ‘recycle’, that happens 9 times out of 13, those being: [17], [16], [18], [72], [82], [87], [94], [95] and [100]. This can create a miscommunication in the scientific community since the terms are not being used as they should.

Table 6 was created using the same articles from Table 5, and presents the end of life options mentioned in each of the articles. The following codes are regarding the ones used on the table and its correspondence.

1: Landfill	12: Hydrolysis
2: Incineration	13: Microwave Assisted Pyrolysis (MAP)
3: Reuse	14: High Voltage Fragmentation (HVF)
4: Mechanical Recycling	15: Blade life extension
5: Pyrolysis	16: Reverse logistics/Producer Responsibility
6: Chemical Recycling	17: Supercritical fluids
7: Thermal Recycling	18: Co-processing
8: Resize/Repurpose	19: Microwave Assisted Chemical
9: Subcritical fluids	20: Hydrolytic recycling
10: Fluidised bed	21: Glycolysis
11: Solvolysis	22: Thermoforming

Table 6: End of life options mentioned in the different articles for wind turbine blades

Article	End of life options																					
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
[17]	x	x	x	x	x	x	x	x	x	x			x				x		x			
[50]	x	x	x	x	x	x	x			x	x	x	x	x	x			x				
[15]	x	x		x			x															
[51]	x	x		x	x	x																
[52]	x	x																				
[53]					x																	
[54]				x	x	x	x			x	x		x				x					
[5]	x	x	x	x	x	x		x		x	x					x						
[55]						x	x															
[7]	x	x		x	x	x				x						x						
[48]	x	x			x	x	x				x											
[56]	x	x			x					x												
[57]	x	x		x	x	x				x								x				
[58]	x	x		x														x				
[59]	x	x		x	x	x	x			x												
[60]	x	x		x														x				
[61]	x			x	x	x	x			x	x		x	x				x				
[62]	x	x		x	x	x	x			x	x							x				
[63]	x	x		x	x	x	x			x	x		x									
[64]	x	x						x														
[65]	x	x		x		x	x											x	x			
[66]	x	x		x	x	x	x			x	x		x				x			x	x	
[16]	x	x		x	x	x	x	x														
[18]		x	x	x	x	x	x			x	x			x	x							
[67]		x		x	x					x	x			x				x				
[68]		x		x		x	x									x						

Article	End of life options																					
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
[69]																						
[70]	x	x		x	x	x				x	x							x				
[71]					x				x		x		x				x					
[72]				x																		
[73]	x	x		x	x	x	x	x		x												
[74]							x															
[75]	x	x				x	x															
[76]	x	x		x																		
[77]				x	x																	
[78]																						
[79]		x		x	x					x	x		x				x					
[80]		x																				
[11]	x	x		x	x	x				x	x	x	x	x	x							
[81]	x	x		x	x		x				x											x
[82]				x	x		x			x												
[13]				x	x	x				x												
[83]	x	x		x	x		x															
[84]	x	x		x	x	x	x			x	x							x				
[85]	x	x				x	x															
[86]	x																					
[87]	x	x		x		x	x															
[88]	x	x		x	x	x				x												
[89]	x	x																				
[6]			x	x		x	x															
[90]			x	x	x	x	x			x							x					
[91]	x			x	x								x									
[19]	x	x		x	x	x	x	x										x				

Article	End of life options																					
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
[92]	x																					
[93]	x																					
[94]	x			x				x										x				
[95]				x																		
[96]	x	x		x	x	x	x			x	x			x				x				
[97]	x							x														
[98]																						
[99]				x		x	x															
[100]	x	x		x	x	x	x			x	x		x	x				x				
[101]																						
[102]																						
[103]				x		x	x															
[104]	x	x		x	x	x				x												
[105]	x		x												x							
[106]	x	x		x																		
[107]				x	x																	

Legend on end of life options code:

1: Landfill
2: Incineration
3: Reuse
4: Mechanical Recycling
5: Pyrolysis
6: Chemical Recycling
7: Thermal Recycling
8: Resize/Repurpose
9: Subcritical fluids
10: Fluidised bed
11: Solvolysis
12: Hydrolysis
13: Microwave Assisted Pyrolysis (MAP)
14: High Voltage Fragmentation (HVF)
15: Blade life extension
16: Reverse logistics/Producer Responsibility
17: Supercritical fluids
18: Co-processing
19: Microwave Assisted Chemical
20: Hydrolytic recycling
21: Glycolysis
22: Thermoforming

Summarizing Table 6, it is possible to see that the five options that are most mentioned are: Mechanical Recycling, Landfill, Incineration, Pyrolysis and Chemical Recycling (Figure 16).

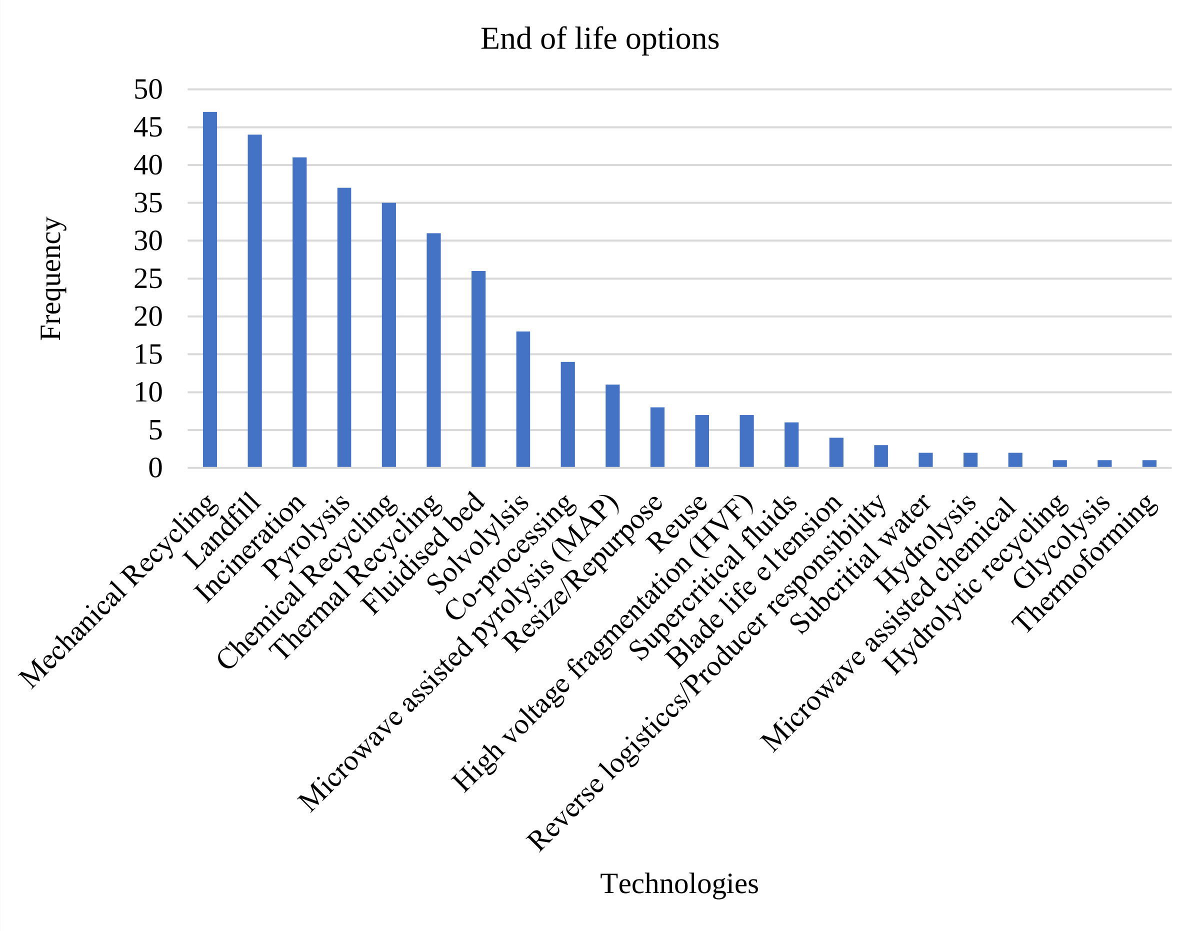

Figure 16: Graphic representation of the most mentioned options for end of life wind turbine blades

It is important to note that it is not because an option is most mentioned that it is the best solution. From the five most mentioned technologies, only three are considered to be a valid option and are available at an industrial scale: Mechanical Recycling, Pyrolysis and Co-processing, as it was mentioned on Table 2.

The mechanical recycling allows the shredded fibers to be used as reinforcement or fillers. The pyrolysis allows the recovery of fiber in the form of ash and of polymer matrix in the form of hydrocarbon products. In the cement co-processing, the glass fiber is used as a component of cement mixes and the polymer matrix is burned as fuel for the process [8].

To date, it has not yet been determined which would be the best method to apply as a route for decommissioned wind turbine blades.

5. CONCLUSIONS AND FUTURE WORKS

As mentioned, wind energy is considered a renewable source of energy and is growing more and more around the world. However, it is important to remember that there are negative sides associated with it. This work aimed to access about the environmental issues related to this energy source.

Despite the studies that have been published since 2009, and the number of projects that have been created to research what to do with wind turbines blades when they reach their end of life, there is no consensual method defined by the scientific community about an alternative route for this waste beside landfill.

During this work, it was mentioned that some countries banned this type of waste from being landfilled, and it is believed that other countries will follow the same step and, as mentioned before, only coming from European offshore wind farms, it is expected 377,052 tons of wind turbine blade waste by the year of 2043 and until now there is no established end-of-life route.

Furthermore, it can be concluded that the scientific community does not have a standard in its studies, which creates a misunderstanding. Many works states basically the same, some of the terms and definitions are not used as it should and vary from one author to another, while the Waste Directive establishes the terms and meanings, which were not followed in 13 of the selected articles for this research.

Even with much research and publications, no certain end of life solution has been established as being ideal. Mechanical Recycling is one of the few technologies available at an industrial scale, but new market for mechanically recycled composites needs to be created [11] [66]. Co-processing in cement kilns seems to see a viable option as well [67] [70]. Another technology is Pyrolysis, and [53] states that is the only technology that allows to recover carbon fibres at an industrial scale.

Albers (2009) was correct when he mentioned that nobody paid attention in the last decade on what would be done when the turbines needed to be dismantled [47]. Until now, there is no defined solution and route to this material.

As a future work, the author would like to update the search results and check if any technology has been considered as the optimal one and available at an industrial scale.

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