The Coming Tide of Wind Turbine Blades Retirement: Threats and Treatment Measures

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Abstract. Wind energy is a kind of clean energy widely used all over the world. Since the 10th of this century, the world has been facing the environmental problem of a large amount of waste produced by retired wind turbines. The blades are difficult to be recycled because of their high strength, corrosion resistance and special materials. The scrapping of wind turbines brings challenges to the sustainable utilization of wind energy. This paper studies the problems brought by the previous methods of treating waste wind turbine blades, including the impact on the surrounding soil and water environment, the emission of air pollutants and greenhouse gases, and the harm to animals, plants and microorganisms in the environment. This paper also introduces the current feasible recovery processes: the mechanical recovery process is relatively simple and has low energy consumption, but the application of the recovered materials is narrow; Thermal recovery can produce widely used products and its by-products have additional value, but the energy consumption is high; Chemical treatment can obtain high-quality recycled products, but the high cost and slow reaction speed make it difficult to deal with a large number of waste blades. The biological treatment methods which has certain application prospect are expected. At the same time, from the perspective of waste generation, this paper studied the recyclable blade materials that includes thermoplastic resin and biomass composites, which provides a feasible way to completely solve the problem of waste wind power blades in the future.

Keywords: wind energy; solid waste; recycling; fiber composite; wind turbine blade.

1. Introduction

Wind energy is one of the most widely used new energy sources in the world. In 2020, wind supplied almost 1600 TWh of electricity, which was over 5% of worldwide electrical generation and about 2% of energy consumption. With the increasing installed capacity, this number will continue to increase. It should expand much faster in the future, by over 1% of electricity generation per year [1]. The service life of wind turbine units is usually between 20 and 30 years, which means that there will be more and more wind turbines decommissioned from the 2010s, and will produce a large amount of solid waste, including wind turbine blades, generators, pillars and concrete foundation. It is estimated that 789,000 tonnes of composite waste will be generated in 2021 and a total of 43 million tonnes by 2050 [2]. The blades are mainly composed of carbon fiber (CF), glass fiber (GF), epoxy resin, polyurethane (PU) adhesive, and internal polymer foam or wood material [3]. The blades are difficult to be recycled because of its high strength, corrosion resistance and special material. The end-of-life (EOL) option of wind turbines brings challenges to the sustainable utilization of wind energy.

Due to the characteristics of thermosetting resin itself, it is almost impossible to recycle it. At present, the existing research mainly focuses on various treatment and recovery processes of waste wind power blades, but there is not much review on the potential environmental and health hazards of these waste blades as solid waste, including the environmental impact caused by stacking and landfill and the pollution caused by open-air incineration. Most of the existing recovery methods aim to destroy the resin part of the composite and recover the fiber. Pu Liu et al. Analyzed different EOL options of waste wind turbine blades in terms of economic benefits [2]; R. Cherrington et al. And K. Ramirez-tejeda et al. Investigated EOL options of waste wind turbine blades in Europe and the United States, and relevant local policies respectively [3,4]. In terms of reuse and recycling of waste blades, Paul t. Mativenga et al. Studied the high voltage fragmentation and mechanical recovery methods of glass fiber reinforced composites (GFRC) [5]; A. M. Nzioka et al. Introduced a method of recovering glass fiber from GFRC by chemical dissolution, and characterized the properties of the obtained fiber products [6]. Pickering SJ et al. Introduced a process of pyrolysis of waste wind power blade materials and recycling fibers in a fluidized bed [7]. At present, there are not many research results on biological treatment methods. N. Eliaz et al. Introduced a possible microbial degradation process to treat epoxy resin [8].

This paper investigates the harm of the traditional treatment methods of waste wind turbine blades to the environment and human health, summarizes the existing treatment methods of the waste blades, and introduces their respective characteristics, application scenarios and shortcomings. At the same time, this paper investigates some treatment methods that have not been put into use but have certain application prospects, and tries to find a means to completely solve the treatment problem of waste wind turbine blades in the future.

2. Potential Hazards of Waste Blades

2.1. Soil Environment

The length of a single wind turbine blade is more than 56 meters, which means that the disposal of these waste blades by landfill will occupy a large area of land (Fig. 1). Due to the high stability of thermosetting resin, the biodegradation of these blades is very slow, which makes the occupied land cannot be reused for a long time. The weight of waste blades will squeeze the soil under the landfill site, reduce its porosity, and reduce its permeability and adsorption. In addition, in the process of landfill, the weak part of the blade or the epoxy resin coating on its surface may fall off due to the effects of temperature, precipitation, soil wear, microorganisms and so on. This is more likely to happen during transportation and cutting. The epoxy resin and polyurethane may become micro plastics and enter the soil. The diffusion of these micro plastics in the soil will change the physical and chemical properties of the landfill site and the surrounding soil, thus affecting the species and quantity of microorganisms in the soil and the ion adsorption performance of the soil [9]. This change will curb the growth of plant roots and the absorption of nutrients in the soil, resulting in the deterioration of the ecological environment in the surrounding areas. Nano scale microplastics can be directly absorbed by the root of plants and enriched along the food chain. Microplastics entering the human body will harm the human immune system, reproductive system and nervous system, and increase the risk of cancer [10].

Fig. 1 A waste wind turbine blade landfill site [11].

Due to the large specific surface area and hydrophobic properties of microplastics, these particles can interact with other pollutants that may exist in the soil and further aggravate the pollution of the soil. At present, a variety of persistent organic pollutants (POPs), heavy metals and antibiotics have been found on the surface of micro plastic particles in soil [9]. Micro plastic particles adsorb and enrich such toxic and harmful pollutants in the soil, and then ingest them into their bodies through plant roots or animals in the soil, which poses a threat to the ecological environment.

2.2. Water Environment

The micro plastic particles or their degradation products produced by waste wind turbine blades can enter the underground or surface water body through the diffusion in the soil or the scouring effect of precipitation. These substances in water will diffuse more easily and affect larger areas with the flow of water. At the same time, the pollutants enriched by micro plastic particles in the soil will also enter the water body with this process, resulting in the rise of heavy metals, COD and other water quality index in the water, making the water quality worse. With the slow degradation of plastic and resin by microorganisms in the water, the COD in the water may also increase, but there is no research shows that this process will have an impact on water eutrophication until now. Similar to the process in the soil, the micro plastic particles in the water are also easy to be ingested by aquatic animals and plants and accumulate in their bodies, then gradually enrich with the food chain, and finally enter the human body.

2.3. Air Environment

Although the abandoned wind turbines blades are difficult to be degraded by microorganisms in soil in a short time, the degradation of organic materials, especially the plastic foam and wood filled with these wastes, will produce greenhouse gases such as methane and two carbon dioxide on a long time scale, making these abandoned blades become carbon sources [8]. In the process of incinerate the waste blades, the combustion of epoxy resin will produce toxic gases such as formaldehyde and carbon monoxide, and will produce a large amount of carbon dioxide emissions [12]. Various additives containing nitrogen, sulfur and halogen in blade materials will also produce nitrogen oxides, sulfur dioxide, halogenated hydrocarbons, dioxins and other air pollutants during combustion. In addition, the nonflammable glass fiber, other ash and carbon in the composites will produce harmful smoke and dust, which will do serious harm to the atmospheric environment. In the process of blade cutting, crushing and grinding, the dust generated will bring risks to the health and safety of on-site staff. Previous studies have shown that inhalation or contact with these dusts through skin and mucous membrane will cause moderate irritation to human body and may lead to respiratory diseases such as cough and asthma [13]. Long term exposure to such dust will lead to pathological changes in human lungs and cause irreversible health damage [14].

2.4. Animals and Plants

Landfill will occupy a large amount of land, this behavior will inevitably occupy the living space of various local animals and plants. Due to the large number of waste leaves, the soil of the landfill site becomes compact and the soil permeability is reduced, which makes it difficult for various animals and plants living in it to obtain oxygen for respiration, resulting in the death of animals and plants in the soil. The micro plastic particles mentioned above will also have a negative impact on animals and plants near the landfill. A study shows that the presence of micro plastic particles such as polyurethane in soil can affect the reproduction rate, growth rate and survival rate of earthworms [15]. Mice exposed to microplastics have symptoms such as liver metabolic disorder, reduced mucin secretion, intestinal flora imbalance and so on [16]. Other pollutants in the soil adsorbed by micro plastic particles may also have toxic effects on animals and plants. Besides, micro plastic particles will migrate from shallow soil to deep soil with the activities of earthworms and other soil animals. In addition to the land occupied can not grow plants, the waste wind turbine blades stacked or buried may also have adverse effects on the surrounding agricultural crops or natural plants. A study on the impact of agricultural plastic film on crops shows that micro plastics such as polyethylene will inhibit the germination of wheat seeds and the growth of seedlings [17]. However, the impact of epoxy resin and polyurethane micro plastics produced by wind power blades on plants is not clear now and needs further research.

2.5. Microorganisms

After the micro plastics and fibers produced by waste wind turbine blades enter the soil, they will change various property parameters of the soil, thus affecting the growth and reproduction of microorganisms in the soil. This organic matter in the soil will improve the position in the competition of a kind of microorganisms which can decompose them as carbon sources, and then change the original microbial community composition of the soil. At present, there is no clear conclusion whether this change is harmful to the soil ecological environment or not. Some additives in the composites can inhibit the proliferation of some soil microorganisms, such as phthalates and bisphenols [18]. These micro plastic particles also provide a carrier for potential pathogenic bacteria in the soil, making it easier for them to migrate to other areas, or enter animals or humans and cause diseases.

3. EOL Options of Waste Blades

3.1. Traditional Disposal Methods

3.1.1 Landfill

The simplest disposal option is to directly bury the waste wind turbine blades underground. The cost of landfill is lower than any other treatment option, which makes it the most widely used disposal scheme of waste wind turbine blades in most regions, including the United States, Europe and China.However, as mentioned above, directly burying these blades will lead to a series of resource and environmental problems, such as land occupation and soil pollution. The EU landfill directive (1999) requires its member states to gradually reduce the level of biodegradable organic waste entering landfills. Germany has banned untreated municipal solid waste from entering landfills since 2005 [3]. Whether from the perspective of resource utilization or environmental protection, landfill is no longer a good method to deal with waste wind turbine blades.

3.1.2 Incineration

Incineration is a method that can effectively utilize the energy of organic components in waste blades and recover the non-combustible glass fibers. Due to the different components of the blades, the calorific value during incineration mainly depends on the proportion of resin material and carbon fiber, ranging from 6MJ / kg to 35MJ / kg [19]. Blades with low content of combustible components can also be mixed with other high calorific value wastes and burned together. Incineration does not need to occupy too much land, and the heat generated can be used for power generation or heating. However, this method also has obvious disadvantages. Firstly, the incinerator can not accommodate large wind power blades. These blades need to be cut and broken in advance before they can be incinerated, and this process will produce additional energy consumption and dust pollution. Secondly, the incineration process will produce carbon monoxide, nitrogen oxides, dioxins and other air pollutants. Although centralized incineration can collect and treat these harmful gases, it will inevitably produce additional costs and energy consumption. In addition, about 60% of the substances after combustion become harmful ash, which still needs to be disposed of separately rather than directly landfilled [4]. In conclusion, incineration treatment can recover the energy and some materials in the waste wind turbine blades to a certain extent, but its economic benefit is low and will lead to great environmental and health risks.

3.2. Recycling Methods

3.2.1 Mechanical Recovery

The mechanical recovery method is mainly to make the waste wind power blades into granular materials by cutting, crushing or grinding and reuse them. Depending on the diameter, these particles are generally used as fillers, building materials (Table 1) or re used in the production of GFRP. These recycled materials can only be used to produce products with low strength requirements, because the crushing process will reduce the length of fiber materials, and reduce the strength of recycled materials. This recovery method has simple process and high commercialization potential, but cutting and shredding high-strength wind power blades requires large energy consumption, and dust pollution will generate dust pollution,which endangering the nearby environment and personnel health.

Table 1 Application Field of Mechanical Recycled Waste Blade Materials [20].

Particle size ranges	Recycling application
>25 mm	Cement board, agricultural ground, building material.
3.2 – 9.5 mm	Covering and soundproofing material: roof asphalt, paving material reinforcing agent, etc.
< 60 μm	Fiber reinforced unsaturated polyester powder moulding compounds (UP-PMC), Bulk molding compound (BMC).

High voltage fragmentation (HVF) method forms small scale high temperature and high pressure through the electric spark generated by high-voltage electric pulse, so as to decompose the blade material and recover the fiber. At present, the research in the laboratory shows that the high voltage fragmentation method can obtain longer and cleaner fiber materials than the traditional mechanical recovery method, but its energy consumption is about 2.6 times more than the traditional mechanical recovery method [5]. This method has certain potential, but it is difficult to be used in large-scale commercial production in a short time.

3.2.2 Thermal Recovery

Thermal recovery methods include pyrolysis and fluidized bed combustion (FBC), which decompose organic components such as resin in waste blades at high temperature and recover the remaining fibers. In the pyrolysis method, the cut blade material is heated to 400-700℃ under the condition of hypoxia, and the products are pyrolytic gas, pyrolytic oil, pyrolytic carbon and fiber. The glass fiber and carbon fiber separated from pyrolytic carbon can be recovered and used, and the pyrolytic gas, pyrolytic oil and pyrolytic carbon can be sold as fuel after certain treatment, or used to provide heat instead of coal or other fuels in the pyrolysis process. The study shows that the high temperature during the pyrolysis process will make the glass fiber lose part of its strength. The strength of the glass fiber obtained by pyrolysis at 450℃ will lose about 50%, and the strength of the fiber obtained at 450-500℃ will lose about 25% [7]. Carbon fiber loses less strength due to the influence of temperature, but the recovered fiber surface is easy to adhere impurities, which has a negative impact on its performance. FBC method is similar to pyrolysis method. In a high-temperature fluidized bed reactor with air as fluidizing gas, the resin components in the waste blades are degraded and the fibers are recovered.

Although some pyrolysis products can be used to provide heat, the energy consumption and carbon dioxide emissions of thermal recovery is much greater than that of mechanical recovery (Fig. 2). However, the products obtained by heat recovery (glass fiber and carbon fiber) are more widely used than mechanical recovery products. Generally, recycled fibers are used to make secondary composites such as vehicle parts and composite plastic sheet or to produce new fibers. At present, the process of blowing the crushed waste wind turbine blade particles into the cement kiln and heating them together with other materials to produce cement has been applied. This process eliminates the process of fiber separation. The combustion of resin components can provide heat for the sintering of cement. Fiber materials help to improve the strength of cement and will not produce additional solid waste [22].

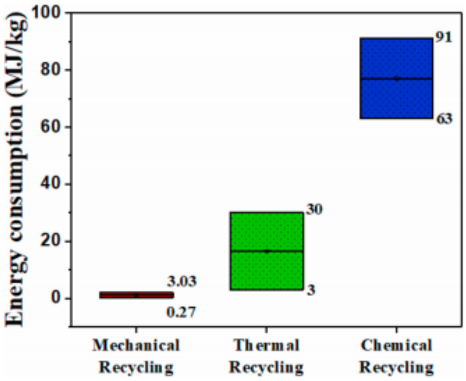

Fig. 2 Energy consumption of different recycling methods [21].

3.2.3 Chemical Recovery

Chemical recovery method usually uses some catalysts to destroy the network cross-linking structure of resin materials, and then adds organic solvents to dissolve the resin components in waste blades and recover fibers. This method can usually obtain very clean fibers, and the mechanical and electrical properties of recycled fibers will not be greatly affected. The recycled carbon fibers obtained by chemical dissolution method can maintain 90% or higher mechanical strength [21]. However, the large amount of solvent and long reaction time of the traditional chemical dissolution method make it difficult to deal with a large number of waste leaves. Due to the need to use some strong acidic chemicals or volatile organic solvents, this method will also have a negative impact on the health of long-term contacts, resulting in an increased risk of respiratory and skin diseases. At the same time, the waste liquid produced after treatment also needs a series of treatment processes to make it harmless, but from another point of view, this provides a possible and feasible way to recover resin components.

At present, there are studies on the recovery process of using supercritical fluid such as supercritical water to replace the traditional solvent to dissolve resin. When potassium hydroxide is added as catalyst, the mechanical strength of recovered carbon fiber can reach 90% ~ 98%, and the resin removal rate can reach 95.3% [23]. Supercritical fluid method can obtain very clean recycled fibers with low mechanical strength loss, and the pollution and health risks are much lower than those of traditional chemical dissolution method. However, supercritical conditions are harsh. Most supercritical fluids require high temperature and high pressure, have strong corrosivity and high requirements for reaction equipment, resulting in high cost and low safety factor. It is only in the laboratory stage until now.

3.3. New Solutions

3.3.1 Biological Treatment

Although thermosetting resin material is difficult to degrade by biochemical reaction compared with thermoplastic resin, this method is not completely impossible because it is still an organic polymer with carbon chain as the main skeleton. Wang et al. studied the degradation process of epoxy resin coating in seawater inoculated with *Pseudomonas putida*, which significantly reduced the strength of epoxy resin coating and formed a complete and mature biofilm [24]. Noam, E et al. isolated two kind of bacteria *Rhodococcus rhodochrous* and *Ochrobactrum anthropi* from the soil near an epoxy resin and polyurethane material factory [8]. Under the synergistic action of these two bacteria, the surface of epoxy resin material can become rough, which means the biodegradation of thermosetting resin materials such as epoxy resin is possible. If strains that are able to degrade epoxy resin materials with high enough efficiency can be found or cultivated, biological treatment will become a low-cost and environment-friendly treatment process of waste wind turbine blades. However, it can be predicted that the reaction rate of biological treatment will not be so fast, so it is difficult to treat a large number of waste blades in a short time.

3.3.2 Other Blade Materials

Thermosetting resin materials are difficult to be recycled or degraded due to their structural characteristics. Now some researchers focus on the development of recyclable materials for wind turbine blades. Obviously, this method can not alleviate the upcoming wave of wind power blade retirement, but in the long run, the promotion of recyclable wind power blades will be of great help to solve this problem. At present, the main recyclable materials include thermoplastic composites and biomass composites. Compared with thermosetting composites, thermoplastic composites have the advantages of recyclability, light weight, good impact resistance and short production cycle, but the fatigue performance in hot and wet environment is poor. The National Renewable Energy Laboratory has developed 61.5m long 5 MW thermoplastic composite wind turbine blades [25]. China, Japan and Europe are also studying the manufacturing process of thermoplastic composite blades. At present, the main challenge faced by thermoplastic composite wind turbine blades is that thermoplastic resin has high requirements for temperature and pressure in the processing process, which makes the production cost and energy consumption of thermoplastic wind turbine blades higher.

Biomass composites mainly use wood or bamboo composites as substitutes for thermosetting composites. Huang et al. studied the properties of Moso Bamboo (*Phyllostachys pubescens*) composites. In addition to density, the properties of this material meet or exceed the characteristics of conventional wood or epoxy laminated wood used in wind power blades at present, which has a certain application potential [26]. The cost of such materials is much lower than that of resin composites when there is sufficient supply of raw materials.

4. Conclusion

This paper investigates the harm of the traditional treatment of waste wind power blades to the environment and human health, so as to prove that the traditional landfill and incineration treatment methods are no longer suitable for use. After that, this paper introduces the existing treatment methods of waste wind turbine blades, and looks forward to two methods to solve the EOL problem of wind turbine blades in the future. Among these waste wind turbine blade treatment schemes, mechanical recovery method has high environmental friendliness, but the application range of recovered products is narrow; Heat treatment technology is relatively mature and has been applied in many cases; Chemical recovery method can obtain complete and clean regenerated fiber, but it has high cost, strict requirements for equipment, and high pollution and health risks; Biological treatment has certain application potential, but there is no suitable process at present. In the future, in order to deal with the increasing number of waste blades, it is necessary not only to select appropriate recycling methods according to the demand, but also to continue to strive to find recyclable blade materials to fundamentally solve this problem.

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