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A circular economy approach to green energy: Wind turbine, waste, and material recovery

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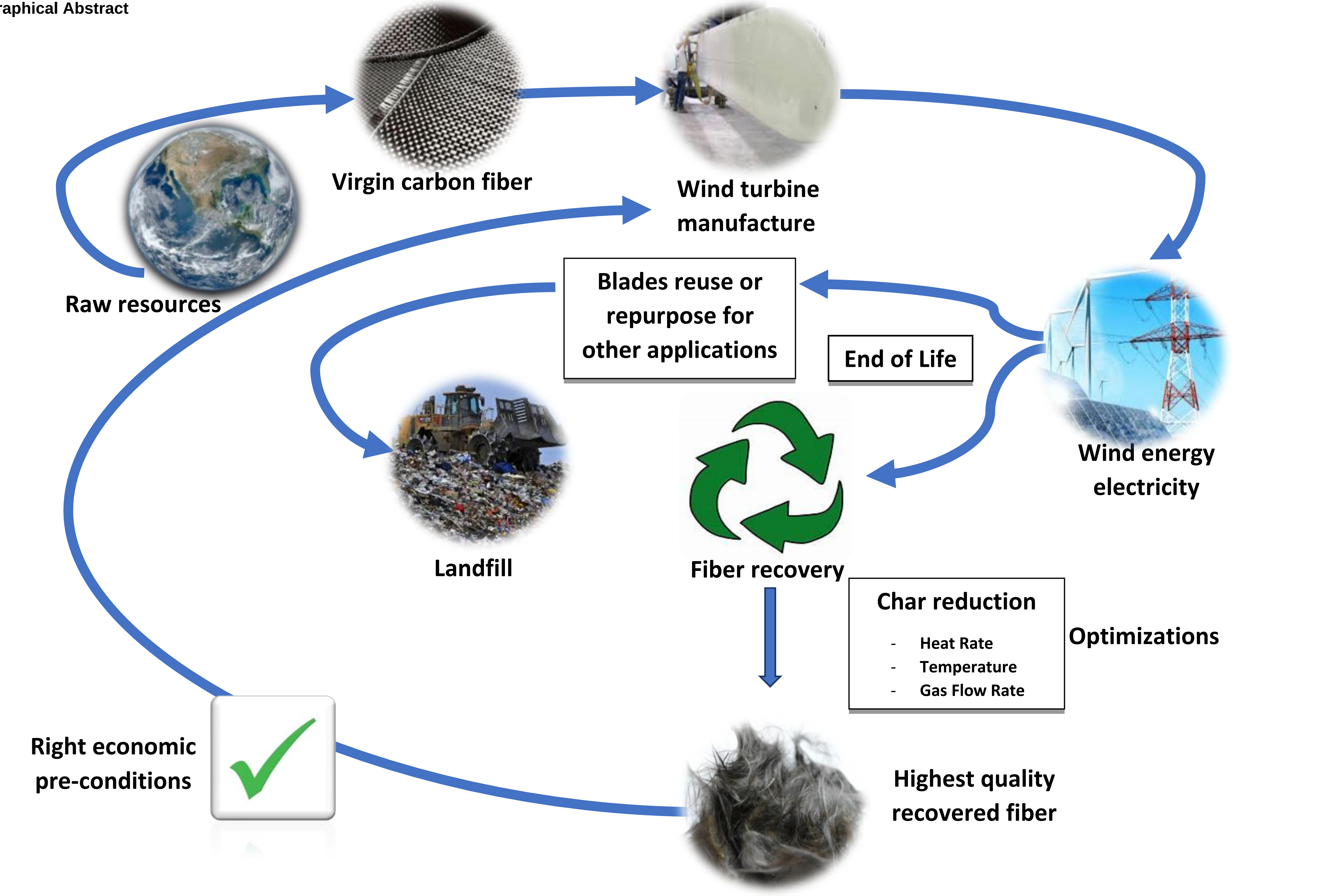
*Graphical Abstract



*Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)

A circular economy approach to green energy: Wind turbine, waste, and material recovery

HIGHLIGHTS

- Four economic preconditions ensure re-entry of recovered fiber into circular system
- Rapid heating rate and high temperature reduce char formation on carbon fiber
- Effect of inert gas flow on reduction of char residues is only obvious at 550°C
- Improved pyrolysis conditions increase char intrinsic reactivity and oxidation rate

A circular economy approach to green energy: Wind turbine, waste, and material recovery

ABSTRACT

Wind energy has been considered as one of the greenest renewable energy sources over the last two decades. However, attention is turning to reducing the possible environmental impacts from this sector. We argue that wind energy would not be effectively "green" if anthropogenic materials are not given attention in a responsible manner. Using the concept of the circular economy, this paper considers how anthropogenic materials in the form of carbon fibers can reenter the circular economy system at the highest possible quality. This paper first investigates the viability of a carbon-fiber-reinforced polymer extraction process using thermal pyrolysis to recalibrate the maximum carbon fiber value by examining the effect of (a) heating rate, (b) temperature, and (c) inert gas flow rate on char yield. With cleaner and higher quality recovered carbon fibers, this paper discusses the economic preconditions for the takeoff and growth of the industry and recommends the reuse of extracted carbon fibers to close the circular economy loop.

HIGHLIGHTS

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- Rapid heating rate and high temperature reduce char formation on carbon fiber
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Keywords:

circular economy, wind turbine, carbon fiber, pyrolysis, recovery, recycling

1. Introduction

Wind energy has been considered as one of the greenest renewable energy sources over the last two decades (Liu and Barlow 2017; Liu et al., 2019). As a result, national and regional energy policies have encouraged the development of onshore and offshore wind farms, where installed capacity has grown rapidly from 7,600 MW in 1998 to 591,000 MW in 2018 (Global Wind Energy Council [GWEC], 2015; 2019). Amidst this growth, attention turns naturally to the environmental impact of end-of-life turbine blades, especially when the end-of-life blades and associated structures end up in landfills and negate the "green" credentials of the industry.

This is a pertinent challenge because the annualized growth rate in wind power over the first decade of the 21st century exceeded 12% (GWEC, 2014) and based on projection, 14.9–18% of global electricity demands will be supplied by wind energy between 2020 and 2050 (European Wind Energy Association [EWEA], 2014; International Energy Association [IEA], 2011). A steady growth scenario of new installation wind farms around the world has been reported by Liu and Barlow (2017) in China, the United States, Europe, and the rest of the world, as shown in Fig. 1. New global installation capacity grew to 51.7 GW in 2014, then 63.8 GW in 2015 but stayed fairly consistent for the next 3 years (54.9 GW in 2016, 53.5 GW in 2017, and 51.3 GW in 2018) in a report by the GWEC (2019).

----- INSERT FIGURE 1 HERE -----

With the rapid growth in wind energy capacities, and considering the typical turbine design lifespan of 20 years, Liu and Barlow (2017) have projected that the end-of-life waste from turbines becomes a critical global problem by 2028. Albers (2009) predicted around 50,000 tons of blade waste in 2020, with the amount exceeding 200,000 tons by 2034. Similarly, Andersen et al. (2014) predicted 400,000 tons of blade waste being generated between 2029 and 2033. Liu and Barlow (2017) estimate the blade material usage in China reaching 1,500,000 tons by 2050. Therefore, there is a pressing need to consider this very significant waste stream.

A typical horizontal-axis unit consists of four main components: a foundation, a tower, a nacelle, and three blades. The nacelle is fabricated from steel and copper. The tower is fabricated from concrete or steel and the foundation is made solely from concrete, with the rotating blades made from composite materials to minimize inertial and windage losses. Considering the anthropogenic materials used, composite is one of the most problematic materials because there are currently no mature recycling channels (Job, 2013; Pimenta and Pinho, 2011).

The composite found in the blades is of fiber-reinforced polymer composite for ease of manufacture into aerodynamic shape and high mechanical performance. However, because of the cross-linked polymer chains in the thermoset matrix, recycling remains a significant challenge, particularly reusing the ingredients in other high-grade applications. Most of the older blades are made of glass-fiber-reinforced polymer (GFRP) composites because of their relatively low manufacturing and material costs. However, this imposes a constraint for recycling options because cost must be tightly controlled to make the recycling process economically viable. To date, the only recycling route that is commercially active is where GFRP waste is shredded and consumed in cement kilns. The value of the waste stream is reduced to that of calcium carbonate, making this approach only viable where landfill is prohibited, as in the case of Germany (Job, 2013).

Because the wind power industry is working toward larger turbines capable of producing 10 MW or greater, weight saving is a primary concern because blade mass increases in proportion to the cube of the rotor radius (Igwemezie et al., 2019). This makes carbon fiber an ideal material because of its high specific stiffness and reduced fatigue sensitivity (Veers et al., 2003). However, the main disadvantage is its high initial cost (Liu and Barlow, 2017). For this reason, carbon-fiber-reinforced polymer (CFRP) has only displaced GFRP in manufacturing structural elements, such as the spar, for blades longer than 45 m. For the next generation of 10 MW units with blades of length 100 m, Wood (2010) notes that the total mass can be reduced by 30% if carbon fiber is used to make blade skins. This mass reduction can potentially mitigate the high cost impact of the material (Veers et al., 2003). Thus, it is recognized that the proportion of carbon fiber composite usage will increase and a trend toward fully carbon composite blades is expected (McKenna et al., 2016). Because carbon fibers are energy intensive to produce and have high intrinsic value, there are both environmental and economic motivations for recovering carbon fibers from CFRP (Shuaib et al., 2015).

In this study, the concept of Circular Economy (CE) is used to consider how the valuable carbon fiber can be recovered from the end-of-life blades and what economic preconditions are required to allow the fiber to reenter the cycle at the highest possible quality. The CE is defined as "an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts towards renewable energy, elimination of toxic chemicals which impair reuse and return to the biosphere, and aims for the elimination of waste through the superior design of materials, products, systems, and business models" (Ellen MacArthur Foundation, 2013). The CE creates a closed-loop system in which resources can be kept in a continuous cycle of production and utility, thereby allowing precious and finite resources to generate more value for an extended period of time (United Nations Environment Program [UNEP], 2006). Hence, moving toward CE necessitates changes in the way we design, produce, consume, use (and reuse), and manage waste.

Some common CE approaches include: (1) recycling and recovery, where used materials are processed or treated so that they can be reused (Hamzaoui-Essoussi and Linton, 2010); (2) remanufacturing, in which worn-out, damaged, or end-of-life products are restored (Wang and Kuah, 2018); (3) sharing or collaborative consumption for optimization of utility (Belk, 2014); and (4) product life extension, in which products are ultimately designed to have a longer lifetime (Tse et al., 2015). These practices require technological improvements and changes to processes, hence most innovation is driven by industry.

This paper does not consider lifetime extension or collaborative consumption possibilities covered by the CE concept, but rather how carbon fiber could reenter the circular economy system at the highest possible quality—either in the forms of a product (reuse/repurpose or resize/reshape) or as recycled "raw" or intermediate material (recycle, recovery, and conversion). Sending end-of-life wind turbine blades to landfill is not a long-term viable solution, where many European Union countries legislate against composite waste being sent to landfills (Pickering, 2006). In response, Asmatulu et al. (2013) explored the reuse of these materials as structural components in bridges, buildings, or artificial reefs. Other ways to repurpose blades may involve bridges or urban furniture, but the key challenge remaining in the reuse of composites in public amenity infrastructure is to ensure structural integrity. In terms of composite blade recycling, the valuable output streams are fiber, filler, resin, and energy recovered (Liu et al., 2019). Blades' recycling typically involves jaw cutters for sectioning before crushing or shredding. Shredding reduces fiber length and strength while hammer milling reduces the composite to smaller fragments, generating noise and dust. The recyclates still contain polymer residue, quality is variable, and applications therefore limited to low-grade structures.

From the CE's perspective, material loop needs to be closed and this very much depends on the quality of the recovered carbon fiber and the technicalities involved (Hahladakis and

Iacovidou, 2018; Kasprzyk and Gajewska, 2019). Clean carbon fibers can be recovered through three known thermal decomposition processes. First, a pyrolysis process, which extracts fibers, energy, and pyrolysate at high temperature in an inert environment. The trade-off of this process is the use of the lowest possible temperature to devolatilize the polymer to avoid fiber degradation (Fraisse et al., 2016). Second is the "fluidized bed" process (Pickering et al., 2015) to decompose the polymer composite thermally. The feedstock is heated to 450–550 °C on a layer of silica sand, fluidized by a flow of hot air, thereby oxidizing and decomposing the polymer matrix. Solvolysis is an alternative process performed using sub- or supercritical fluids. This strips the polymer matrix via a chemical reaction in an aggressive solvent attack. Pure carbon fibers, an inorganic residue, and low molecular weight hydrocarbons are the typical output streams (Sokoli et al., 2018).

Among the three recovery options, pyrolysis has been the process of choice in recent decades. Unlike the fluidized bed process technology, which burns off the organic matrix for energy recovery, the pyrolysis process recovers both fiber and a hydrocarbon stream for potential reuse. Although low-cost solvents are used in solvolysis, a high energy intensity of up to 101 MJ/kg (La Rosa et al., 2016) is required to achieve the high pressure and temperature conditions, thus limiting their progress to the laboratory scale. In contrast, the energy requirement for a typical pyrolysis process is much lower at around 30 MJ/kg (Witik et al., 2013) and compares favorably to virgin carbon fiber production, which consumes 704 MJ/kg (Das, 2011). Microwave-assisted heating may also yield energy saving compared with conventional convective furnaces (Jiang et al., 2015). Fiber recovered from the pyrolysis process is relatively clean, with low levels of char residue, and around 90% property retention (McConnell, 2010). These fibers also bond well to epoxy resin (Jiang and Pickering, 2016), making them reusable in new composites.

Despite its growing popularity, few reports address the effect of pyrolysis conditions on the quality of the recovered fiber. Meyer et al. (2009) focused on the effects of pyrolysis temperature, dwell time, and oven atmosphere on the performance of recovered carbon fibers, while Lyon (1998) studied char residuals and their dependence on resin chemistry. A conventional pyrolysis process will result in char formation, which requires a second oxidative treatment (Meyer et al., 2007) because it inhibits free fiber handling and dispersion quality in intermediate products such as nonwoven mat (Wong et al., 2012) and compromises adhesion strength. Lower oxidation temperature and short oxidation times seem to assist char minimization and fiber strength retention (Yang et al., 2015). Clearly, minimizing char residues is critical, along with minimizing oxidative damage to the fiber.

It is evident that carbon fiber recovery from end-of-life blades is a critical issue for greener and more sustainable wind energy production, where successful carbon fiber recovery through pyrolysis is very promising to create and close the circular economy loop. The presence of char residues affects the quality of recovered carbon fibers and posttreatment processes are needed, which add additional cost and complexity to the recovery of fibers. To achieve this, we determine the pyrolysis conditions that lead to ideal recovered fibers, which could reenter the circular economy system at the highest possible quality and without any secondary cleaning.

Hence, this paper investigates the potential of CFRP recovery and the quality of the recovered materials. To close the CE loop, the technicalities and economics of extraction are considered, alongside the potential applications of recovered fibers. The paper is organized as follows: Section 2 presents the method to determine the pyrolysis conditions that lead to ideal recovered fibers, which could reenter the circular economy system at the highest possible quality. Section 3 presents the results; while Section 4 discusses the recovery costs, economic preconditions, and considerations for fiber applications. Section 5 concludes.

2. Methodology

The effects of pyrolysis temperature, heating rate, and nitrogen flow rate on char volume were investigated using a thermogravimetric analyzer (TGA). Then, the oxidation rate of the produced char, as expressed in terms of intrinsic reactivity, was measured via a nonisothermal approach. The morphology of the char was then studied via a scanning electron microscopy (SEM) analysis.

2.1 Materials

Unidirectional prepreg Toray® T700s carbon fibers and 37 wt% epoxy resin were supplied by Aojing Composite Company, Shanghai, China. The prepreg was cut to 200 mm by 200 mm and cured at 140 °C in air for 2 h. The release film and backing paper were removed before the prepreg was pyrolyzed using a TGA. To study the char oxidation rate, epoxy was squeezed out from the as-received prepreg between hot platens at 5 MPa and 80 °C. The resin was cured at the previous schedule and subjected to thermal analysis, as described below.

2.2 Thermal analysis

Thermal and degradation properties of the cured prepreg were investigated using an SDT Q600 TGA from TA Instruments, Delaware, US, on approximately 20 mg samples in a nitrogen environment according to the heating profiles summarized in Fig. 2. Samples were heated from ambient to either 550 °C or 650 °C, after which the samples were held isothermally for 30 min before cooling to room temperature. A range of heating rates were used in this study. The slowest heating rate was decided according to the common practice in lab-scale pyrolysis studies on composite waste, which is between 10 and 30 °C/min (Onwudili et al., 2016; Song et al., 2017), thus it was set to 20 °C/min. The highest heat rate was determined by the capability of the TGA unit, i.e., 200 °C/min. Other selected heating rates were 80 and 100 °C/min, which are common in fast pyrolysis studies on biomass (Wang et al., 2019) and coal (Jiang et al., 2019). The weight loss profile of the degrading sample under these four different heating rates was recorded. These tests were undertaken at a constant nitrogen gas flow rate of 50 ml/min. However, in the later stage of the study, the nitrogen gas flow rate was increased to 100, 200, and 400 ml/min with other process variables unchanged.

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Char oxidation kinetics was studied by subjecting the neat epoxy to the same thermal cycles as shown in Fig. 3 to create different grades of char. The gas flow was maintained at 50 ml/min. The pyrolytic chars were later dried and subjected to an intrinsic reactivity test and SEM analysis, as detailed below.

2.3 Char analysis

The combustion characteristics of carbonaceous residue were determined using an intrinsic reactivity analysis with nonisothermal heating in air (Unsworth et al., 1991). Pyrolytic char samples were heated from ambient temperature to 105 °C inside an air-filled chamber at a heating rate of 20 °C/min. The temperature was maintained for 30 min for moisture removal and then ramped to 900 °C at the same heating rate to complete the intrinsic reactivity study. Mass loss profile (TG) and the first derivative of the mass loss profile (DTG) were analyzed to identify peak temperature (PT) and burnout temperature (BT) of the pyrolytic char sample. The peak of the DTG curve was used to determine the PT value because it is defined as the temperature at which the highest combustion rate occurs. The BT is defined at 1 wt%/minute of combustion rate. A Zeiss@ Sigma VP scanning electron microscope was used to study the morphology of pyrolytic char with a 10 kV accelerating voltage.

3. Results

3.1 Effects of heating rates and pyrolysis temperatures

TGA mass loss profiles are shown in Fig. 4, which clearly demonstrate that after a marginal drop during early-stage heating, each of the profiles undergoes a sharp drop in mass before finally reaching a plateau region. The initial drop was mainly due to moisture loss, while conversion of the epoxy matrix into volatiles produced the sharp loss in mass and the rate of conversion, which is accelerated at higher pyrolysis temperatures. A portion of the epoxy matrix was converted into pyrolytic char and remained on the surface of the carbon fiber. Together, they contributed to the final masses at the plateau region as shown in Fig. 3, which vary with heating rates and pyrolysis temperatures. Because the carbon fiber reinforcement was relatively unaffected by the pyrolysis process, the variations in final mass loss corresponded to the extent of char retention.

----- INSERT FIGURE 3 HERE -----

The variations in mass loss are further illustrated in Fig. 5, recalling the initial epoxy loading of 36.4 wt%. A mass loss exceeding 36.4 wt% suggests degradation of the carbon fiber, but a lower value indicates the presence of pyrolytic char. At 550 °C, a mass loss of 28.0 wt% was recorded at 20 °C/min and a further 5 wt% reduction was achieved by ramping the heating rate to 200 °C/min, which suggested the fiber residue entrained 3.5 wt% of char. Lower char contents were obtained at the higher pyrolysis temperature of 650 °C and again, higher heating rates resulted in greater mass loss, but the rate effects were lower than that at 550 °C. Bridgwater and Peacocke (2000) have reported the significance of these two factors on the mass distribution of char and volatiles from biomass, typically a higher heating rate and pyrolysis temperature favored the production of gaseous products and the reverse conditions favored char formation due to secondary coking and repolymerization reactions. These agree with the findings reported in Fig. 4, and because the aim of the project is to reduce char formation, this can be achieved with higher heating rate and/or increasing the pyrolysis temperature from 550 °C to 650 °C. The former factor is preferable because higher temperatures are likely to degrade the carbon fiber performance.

----- INSERT FIGURE 4 HERE -----

3.2 Effect of nitrogen gas flow rate

Fig. 5 shows the mass loss curve for prepreg at different nitrogen gas flow rates for two different pyrolysis temperatures. It can be seen in Fig. 5(a) that at a pyrolysis temperature of 550 °C, more volatiles were released, or fewer char residues were left on the fiber when the gas flow rate was increased from 50 ml/min to 200 ml/min for both 20 °C/min and 80 °C/min heating rates. Higher flow rate suggests shorter residence time within the heating chamber for volatiles and this reduces secondary reactions that promote char formation (El-Harfi et al., 1999; Pütün et al., 2006; Uzun et al., 2007) or cracking of the primary volatiles and repolymerization in hot char particles (Lanzetta et al., 1997). However, no further significant mass loss was observed with gas flow rate higher than 200 ml/min. In contrast, the dependency of mass loss on gas flow rate became less extensive at a heating rate above 100 °C/min. Previous studies again support this finding, e.g., a shortened volatiles' residence time was observed by Montoya et al. (2015) in depolymerization reactions of cellulose and hemicellulose. In another case, which focused on pyrolytic behavior of rapeseed, Haykiri-Acma et al. (2006) found that a higher heating rate reduced volatiles' residence time, which could further reduce secondary reactions such as cracking, repolymerization, and recondensation. Our results are consistent with these studies because greater mass loss accompanied higher heating rates and the volatiles' residence time was expected to be greatly reduced and become independent of nitrogen flow rate for a heating rate above 100 °C/min.

Similar tests on the effect of gas flow rate were repeated at a higher pyrolysis temperature of 650 °C. However, as plotted in Fig. 5(b), a rather complex relationship is observed. At 20 and 80 °C/min heating rates, char mass loss increased gradually to 32.4% and 33.6%, respectively, with increasing gas flow rate to 200 ml/min, but the mass loss started to decline with further increase in flow rate to 400 ml/min. A general trend toward higher mass loss, despite not being as evident as the results at 550 °C, can be identified for 100 and 200 °C/min heating rates. Overall, the impact of the gas flow rate was less apparent at 650 °C.

----- INSERT FIGURE 5 HERE -----

3.3 Intrinsic reactivity analysis of char oxidation rate

Fig. 6 shows the effects of pyrolysis temperature and heating rate on chars' intrinsic properties; at either 550 °C or 650 °C, both PT and BT reduce with higher heating rates, which indicates char resulting from higher heating rate was more reactive and could be oxidized at a lower temperature. In addition, higher pyrolysis temperatures increased the BT value provided the heating rate was less than 100 °C/min. Consistent with this, Chitsora et al. (1987) reported such an effect in relation to German bituminous coal char produced in a fluidized bed, similarly on lignite char by Ashu et al. (1978).

----- INSERT FIGURE 6 HERE -----

3.4 Scanning electron microscopy

The effects of heating rates and pyrolysis temperatures on the morphologies of pyrolytic char are depicted in SEM images shown in Fig. 7. It is evident that the combination of low heating rate and low pyrolysis temperature, as shown in Fig. 7(a), created char with a rough but continuous appearance. However, at 650 °C, as shown in Fig. 7(b), porosity became apparent, increasing with higher temperature and heating rate. Fushimi et al. (2003) suggested that a high heating rate caused a rapid evolution of volatiles, which in turn increased the porous structure. Fast volatile release rate produced considerable overpressure, which encouraged void coalescence and greater porosity levels (Guerrero et al., 2005). Septien et al. (2018) reported that a high porosity level would enhance gas species diffusion within the char open structure, which facilitated penetration of oxygen and better evacuation of reaction products from the porous structure. Char created from the epoxy matrix in this study reinforced their findings because a high intrinsic reaction was found from char with a high porosity.

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4. Discussion

Section 3 reported that a rapid heating rate caused a substantial reduction of pyrolytic char volume, particularly for pyrolysis at 550 °C. The inert-gas flow rate was another contributing factor to char yield and the level at which it affected the char content depended on the pyrolysis temperature and heating rate. Higher gas flow rate promoted devolatilization and reduced the char content provided the heating rate was less than 100 °C/min and the pyrolytic temperature was 550 °C. However, the positive effect became insignificant at higher temperature and heating rate. The intrinsic reactivity of the char was significantly influenced by the pyrolytic reaction conditions. Char with higher intrinsic reactivity was associated with high heating rates and temperature and this implied the char had a faster oxidation rate. These findings are of commercial relevance to the carbon fiber recycling industry with high priority in cost control because with a lower char volume and faster oxidation kinetics, the energy-intensive oxidation process can be shortened and the carbon fiber can potentially be recovered with a higher mechanical performance due to the compressed thermal cycle. The importance of recovery cost and the reuse options available for the recovered carbon fiber will be discussed in subsequent sections.

4.1 Recovery costs

Presently, there is no industrial-scale recycling of end-of-life turbine blades; therefore, the costs and actual commercialization procedure have not been well-defined (Larsen, 2009). Research on recycling and remanufacturing of these items is still ongoing. Pyrolysis is a mature fiber recovery approach and has been considered suitable for mass-scale commercial efforts use (Rybicka et al., 2016). Existing pyrolysis practices require size reduction and progressively shorter fibers (and lower value) as the number of cycles increases. Thus, the hierarchy of applications ranges from initial, continuous fiber composites, ultimately to milled fiber fillers for lower grade structures. This potential circular economy flow is illustrated in Fig. 8.

----- INSERT FIGURE 8 HERE -----

The materials CE loop sets some economic preconditions for the retrieval of carbon fibers. At the initial stages, without a demand-side pull, legislative drivers, or standards in the reuse of materials, private sector investments are unlikely. Furthermore, implementing recycling and recovery comes at a price, including the collection costs, pretreatment and sorting costs, and the costs of final recovery.

However, the market value of the recovered carbon fiber and concomitant by-products could offset many of these costs. This is because the production process of virgin carbon fibers is energy intensive, and incurs high manufacturing cost, especially in the case of high-grade carbon fiber (used for structural applications such as blades). Therefore, there is a greater economic incentive to recover these carbon fibers. Moreover, the costs of commercially available fibers reclaimed through pyrolysis have been reported by industry sources to be about 10 Euros per kg while the market value of virgin product is 18–50 Euros per kg (ELG Carbon Fiber, 2016).

Industry perspectives also agree that the cost to recover carbon fiber will be a fraction of that for producing virgin carbon fiber (Carberry, 2008). The energy requirement to recover carbon fibers (Cherrington et al., 2012; Vo Dong et al., 2018) is typically <10% that of virgin fiber production[1]. Previous studies also highlighted the importance of throughput in reducing the unit cost through a recycling plant (Meng et al., 2018). Clearly, the energy requirements, efficiency, and cost associated with recycling the carbon fibers from blades would improve beyond the current reported (laboratory) figures in mature, mass production settings.

4.2 Economic preconditions needed

As the technology for recovery and up-scaling of recycling continues to be developed, there are four considerations that need to be addressed to enable the takeoff and growth in the recovery of carbon fibers from end-of-life blades.

First, there must be a network to ensure a consistent supply of feedstock for fiber recovery that would deliver economies of scale. The current lack of infrastructure for collecting end-of-life blades is a key challenge. Ideally, recycling facilities should be located close to wind farms; alternatively, mobile recycling units have been trialed in some regions. Sorting and classification will also improve value streams. Nonstandard construction (Brøndsted et al., 2005) means that traceability would help to identify ideal processing parameters, likely yield, etc.

Second, a marketplace must be created for secondary or recovered materials (Stahel, 2013) to centralize demand for recyclates or fibers produced. The market demand for the materials will help to offset the cost of decommissioning and collecting end-of-life blades. The concept of CE necessitates that there is a ready market to receive and reintroduce the recovered materials into the economic cycle (Wang and Kuah, 2018). There could be an issue

[1] 286 MJ/kg (Suzuki and Takahashi, 2005) and 704 MJ/kg (Das, 2011)

if the cost of virgin materials is already low as in the case of glass fibers. The recovered materials must have a value higher than the cost needed to retrieve them, i.e., using recovered fibers must be cheaper than the cost of using virgin materials directly. This is the most likely case for carbon fibers.

The recent agreement in providing composite waste from Boeing's aircraft manufacturing facilities to ELG Carbon Fiber signaled both the value of composite waste supply and the availability of a marketplace for the recovered fiber (Zazulia, 2018). Fiber recovered from the manufacturing wastes and growing end-of-life parts can potentially help in mitigating the shortage in virgin fiber supply, particularly in the demand for discontinuous fibers. Recyclers have been developing scalable conversion technologies to enlarge the supply-side capacity for recovered fiber. For example, a new hybrid nonwoven mat containing recovered carbon fiber and polyamide 6 resin was developed for making seatbacks for the high-volume automotive applications (Milberg, 2017). Driven by the affordability (Nicolais and Pisanova, 2012) and more environmentally friendly recovery process, more reuse applications in the near future are anticipated.

Third, quality standards for the fibers or recyclates must be established to build confidence (Carberry, 2008; Finnveden et al., 2013; Job, 2013; Pickering, 2006; Wood, 2010). The design of a product, the material retrieval system, efficiency of sorting, and the recovery technology are fundamental in increasing the quantity, quality, and usability of recovered materials (Gregson et al., 2015).

Fourth, key legislation and government policy intervention need to mandate both operators and end-users into the reuse of recovered carbon fiber with accompanying fiscal penalties and benefits. Cherrington et al. (2012) outlined some of the key examples of legislation and directives relevant to end-of-life blades. Landfill and incineration disposal are increasingly penalized (Cherrington et al., 2012) whilst R&D incentives for sustainable product design and technologies that enhance the recycling process (Söderholm and Tilton, 2012) are increasingly important. Extended Producer Responsibility (EPR) is another important initiative to encourage further recycling, where producers play a more proactive role in supporting recovery and reuse. EPR has been successfully utilized for end-of-life vehicles and waste electrical and electronic equipment (Cherrington et al., 2012).

4.3 Recovered carbon fibers' applications and considerations

Low-grade application:

Granulation of CFRP scrap requires the lowest energy of all recovery methods (Wong et al., 2017). These recyclates can be sorted into resin-rich and fibrous-rich groups, but both have low commercial value because the recyclates still contain a high level of resin residues, limiting their usage to low-grade applications, such as being used as a filler for polymer resin or construction materials (Thomas et al., 2014) and concrete (Mastali and Dalvand, 2016).

Medium-grade application:

To maximize the value of recovered carbon fibers, they should be separated from the polymer matrix and the fiber should retain enough mechanical performance for the next application. To date, this can be achieved via the common pyrolysis process and with the use of adequate pyrolytic conditions; as discussed in this paper, cleaner and stronger carbon fibers can potentially be recovered. However, blades are bulky, and to reduce logistical cost, decommissioned blades are sectioned in situ to a manageable size for transportation to recycling facilities, at which, further size reduction has taken place prior to feeding to the pyrolysis process.

As a result, the recovered fibers are generally short and fluffy and cannot be processed in the same way as the virgin fibers. To allow the fibers to reenter the circular economy system at the highest possible quality, they should be converted into intermediate forms suitable for industrial molding processes.

Nonwoven mat is a common intermediate form widely offered by the recycling industries, which can be made by carding and spinning or papermaking. Both are cost-effective processes, suited to mass volume production and with versatile combinations of thermoplastic filaments or powders suitable for thermoforming (Wolling et al., 2017). Because of the random orientation of fibers, the fiber packing density is limited to around 30% (Wong et al., 2017). Nonwovens are typically used in nonstructural applications, such as tooling for aerospace parts (Gardiner, 2014), heating elements (Pang et al., 2012), and electromagnetic interference shielding (Wong et al., 2010).

Higher-grade application:

Fiber alignment is a necessary intermediate step for higher-value applications because the presence of a close-packed structure greatly increases the reinforcing potential of the fibers. Hydrodynamic alignment was originally developed in the 1970s (Bagg et al., 1977) but more recent innovations (e.g., van de Werken et al., 2019; Wong et al., 2009) optimize streamline velocities to deposit an aligned fiber slurry onto a moving mesh. Clean, free-flowing filaments are essential here, underlining the need for a char-free feedstock, because char carryover inhibits uniform dispersion, hence the need for upstream control of pyrolytic conditions, as reported here.

Other alignment technologies include electrostatics (Ravindran et al., 2018), air streaming (Ericson and Berglund, 1993), and the dry carding process (Miyake and Imaeda, 2016). Fiber alignment plays an important role in upgrading the value of the recovered carbon fiber but, clearly, production economics remains to be established for any of these secondary operations.

5. Conclusions and Recommendations

This paper is the first to consider urban mining of carbon fiber from end-of-life wind turbine blades to close the CE loop. Using the concept of CE in reusing, repurposing, recycling, and recovering, this paper investigates CFRP recovery and the quality of the recovered materials.

Our investigation revealed that pyrolytic reaction conditions were important in controlling char formation volume and its oxidation rate. A rapid heating rate caused a substantial reduction of pyrolytic char volume, particularly for the pyrolysis process undertaken at 550 °C. Nitrogen gas flow rate also affected the char content at a specific combination of pyrolysis temperature and heating rate. At 550 °C and less than 100 °C/min heating rate, a higher gas flow rate favored the devolatilization process and reduced the char content. High heating rate and pyrolysis temperature produced char with higher intrinsic reactivity, suggesting a faster oxidation rate. This is beneficial to shorten the post-processing step, thereby leading to lower energy costs. These findings are of commercial significance to the carbon fiber recycling industry with high priority in cost control as with lower char volume and faster oxidation kinetics, and hence the carbon fiber can potentially be recovered with a higher mechanical performance due to the shortened thermal cycle.

Creating a market and closing the CE loop requires several issues to be overcome so that recovered carbon fibers can be accepted as an environmentally friendly, reliable, and cost-effective material. The industry would require establishment of standards for the recycled carbon fiber products and to regulate pyrolysis operations. In addition, a labeling scheme such as those used in recycled plastics would yield greater user acceptance and support. This addresses the demand-side conditions. Further fiscal incentives and penalties by governments would also push the supply side so that companies might engage more responsibly in closing the circular loop.

Our investigation also identifies scope for future studies. This investigation looked into maximum carbon recovery for first-time recycled carbon fiber. Carbon fiber physical and mechanical properties will degrade over time after multiple thermal treatments, hence affecting their reuse value. Therefore, a more detailed study is recommended to encompass this complex scenario of having different stages of recovered fiber content to ensure long-term sustainability. Second, the thermal pyrolysis of carbon fiber produces two other by-products—oil and gas—that have good calorific and some economic value. Clearly, further study of these by-products would assist a full loop recycling solution for the composite wastes.

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References

Albers, H., 2009. Recycling of wind turbine rotor blades - fact or fiction ? DEWI Magazine. 34, 32–41.

Andersen, P.D., Bonou, A., Beauson, J., Brondsted, P., 2014. Recycling of wind turbines, In Larsen, H.H., Petersen, L.S. (eds) DTU International Energy Report 2014: Wind energy — drivers and barriers for higher shares of wind in the global power generation mix, pp 91-97.

Ashu, J.T., Nsakala, N.Y., Mahajan, O.P., Walker Jr, P.L., 1978. Enhancement of char reactivity by rapid heating of precursor coal. Fuel. 57 (4), 250-251.

Asmatulu, E., Twomey, J., Overcash, M., 2013. Recycling of fiber-reinforced composites and direct structural composite recycling concept. Journal of Composite Materials. 48(5), 593–608.

Bagg, G.E.G., Cook, J., Dingle, L.E., Edwards, H., Ziebland, H., 1977. Manufacture of composite materials. Google Patents.

Belk, R., 2014. You are what you can access: sharing and collaborative consumption online. Journal of Business Research. 67 (8), 1595-1600.

Bridgwater, A.V., Peacocke, G.V.C., 2000.Fast pyrolysis processes for biomass. Renewable and Sustainable Energy Reviews. 4(1), 1-73.

Brøndsted, P., Lilholt, H., Lystrup, A., 2005. Composite materials for wind power turbine blades. Annual Review of Materials Research. 35(1), 505-538.

Carberry, W., 2008. Airplane Recycling Efforts benefit boeing operators. Boeing Aero Magazine QRT. 4(08), 6-13.

Cherrington, R., Goodship, V., Meredith, J., Wood, B.M., Coles, S.R., Vuillaume, A., Feito-Boirac, A., Spee, F., Kirwan, K., 2012. Producer responsibility: Defining the incentive for recycling composite wind turbine blades in Europe. Energy Policy. 47, 13-21.

Chitsora, C.T., Mühlen, H.J., van Heek, K.H., Jüntgen, H., 1987. The influence of pyrolysis conditions on the reactivity of CHAR in H2O. Fuel Processing Technology. 15, 17-29.

Das, S., 2011. Life cycle assessment of carbon fiber-reinforced polymer composites. The International Journal of Life Cycle Assessment. 16(3), 268-282.

El-Harfi, E., Mokhlisse, A., Chanâa, M.B., 1999. Effect of water vapor on the pyrolysis of the Moroccan (Tarfaya) oil shale. Journal of Analytical and Applied Pyrolysis. 48(2), 65-76.

ELG Carbon Fibre, 2016. Recycled Carbon Fibre as an Enabler for Cost Effective Lightweight Structures. http://www.elgcf.com/assets/documents/GALM_US_2016.pdf. (Accessed 2/5/2019).

Ellen MacArthur Foundation, 2013. Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. Ellen MacArthur Foundation, Isle of Wight.

Ericson, M.L., Berglund, L.A., 1993. Processing and mechanical properties of orientated preformed glass-mat-reinforced thermoplastics. Composites Science and Technology 49(2), 121-130.

EWEA, 2014. Wind energy scenarios for 2020, pp.1–8. http://www.ewea.org/fileadmin/files/library/publications/scenarios/EWEA-Windenergy-scenarios-2020.pdf

Finnveden, G., Ekvall, T., Arushanyan, Y., Bisaillon, M., Henriksson, G., Gunnarsson Östling, U., Söderman, M., Sahlin, J., Stenmarck, Å., Sundberg, J., 2013. Policy instruments towards a sustainable waste management. Sustainability. 5(3), 841-881.

Fraisse A, Beauson J, Brøndsted P, Madsen B., 2016. Thermal recycling and re-manufacturing of glass fibre thermosetting composites. In: Proceedings of the 37th Risø international symposium on materials science.

Fushimi, C., Araki, K., Yamaguchi, Y., Tsutsumi, A., 2003. Effect of heating rate on steam gasification of biomass. 1. Reactivity of char. Industrial & Engineering Chemistry Research. 42(17), 3922-3928.

Gardiner, G., 2014. Recycled carbon fiber update: closing the CFRP lifecycle loop. Composites Technology 20(6), 28-33.

Gregson, N., Crang, M., Fuller, S., Holmes, H., 2015. Interrogating the circular economy: the moral economy of resource recovery in the EU. Economy and Society 44(2), 218-243.

Guerrero, M., Ruiz, M. P., Alzueta, M. U., Bilbao, R., Millera, A., 2005. Pyrolysis of eucalyptus at different heating rates: studies of char characterization and oxidative reactivity. Journal of Analytical and Applied Pyrolysis. 74(1-2), 307-314.

GWEC, 2014. Market forecast for 2014 - 2018, Brussels. http://www.gwec.net/wp-content/uploads/2014/04/Market-forecast-2014-2018.pdf.

GWEC, 2015. Global Wind Report Annual Market Update 2014. http://www.gwec.net/wpcontent/uploads/2015/03/GWEC_Global_Wind_2014_Report_LR.pdf.

GWEC, 2019. Global Wind Report 2018. https://www.gwec.net/wp-content/uploads/2019/04/GWEC-Global-Wind-Report-2018.pdf

Hamzaoui-Essoussi, L., Linton, J.D., 2010. New or recycled products: how much are consumers willing to pay? Journal of Consumer Marketing. 27 (5), 458-468.

Hahladakis JN, Iacovidou E., 2018. Closing the loop on plastic packaging materials: What is quality and how does it affect their circularity? Science of the Total Environment. 630, 1394-1400.

Haykiri-Acma, H., Yaman, S., Kucukbayrak, S., 2006. Effect of heating rate on the pyrolysis yields of rapeseed. Renewable Energy. 31 (6), 803-810.

Igwemezie, V., Mehmanparast, A.,Kolios, A., 2019. Current trend in offshore wind energy sector and material requirements for fatigue resistance improvement in large wind turbine support structures–A review. Renewable and Sustainable Energy Reviews. 101, 181-196.

IEA, 2011. Wind Energy Technology Roadmap, Springer-Verlag, Berlin, Heidelberg.

Jiang, G., Pickering, S.J., 2016. Structure–property relationship of recycled carbon fibres revealed by pyrolysis recycling process. Journal of Materials Science. 51(4), 1949-1958.

Jiang, L., Ulven, C. A., Gutschmidt, D., Anderson, M., Balo, S., Lee, M., Vigness, J., 2015. Recycling carbon fiber composites using microwave irradiation: Reinforcement study of the recycled fiber in new composites. Journal of Applied Polymer Science, 132(41). 42658.

Jiang, Y, Zong, P., Tian, B, Xu, F., Tian, Y., Qiao, Y., Zhang, J., 2019. Pyrolysis behaviors and product distribution of Shenmu coal at high heating rate: A study using TG-FTIR and Py-GC/MS. Energy Conversion and Management,179, 72-80.

Job, S., 2013. Recycling glass fiber reinforced composites - History and progress. Reinforc Plast. 57(5), pp.19–23.

Kasprzyk M, Gajewska M., 2019. Phosphorus removal by application of natural and semi-natural materials for possible recovery according to assumptions of circular economy and closed circuit of P. Science of The Total Environment. 650, 249-256.

La Rosa, A.D., Banatao, D.R., Pastine, S.J., Latteri, A., Cicala. G., 2016. Recycling treatment of carbon fibre/epoxy composites: Materials recovery and characterization and environmental impacts through life cycle assessment. Compos. B Eng. 104, 17-25

Lanzetta, M., Di Blasi, C., Buonanno, F., 1997. An experimental investigation of heat-transfer limitations in the flash pyrolysis of cellulose. Industrial & Engineering Chemistry Research. 36(3), 542-552.

Larsen, K., 2009. Recycling wind turbine blades. Renewable Energy Focus. 9(7), 70-73.

Liu, P., Barlow, C. Y., 2017. Wind turbine blade waste in 2050. Waste Manag. 62, 229-240.

Liu, P., Meng, F., Barlow, C.Y., 2019. Wind turbine blade end-of-life options: An eco-audit comparison. J. Clean. Prod. 212, 1268-1281.

Lyon, R.E., 1998. Pyrolysis kinetics of char forming polymers. Polymer Degradation and Stability. 61(2), 201-210.

Mastali, M., Dalvand, A., 2016. The impact resistance and mechanical properties of self-compacting concrete reinforced with recycled CFRP pieces. Compos. B Eng. 92, 360-376

McConnell, V.P., 2010. Launching the carbon fibre recycling industry. Reinforc. Plast. 54, 33-37.

McKenna, R., vd Leye, P. O., Fichtner, W., 2016. Key challenges and prospects for large wind turbines. Renewable and Sustainable Energy Reviews. 53, 1212-1221.

Meng, F., McKechnie, J., Pickering, S.J., 2018. An assessment of financial viability of recycled carbon fibre in automotive applications. Compos Part A: Appl Sci Manuf. 109, 207-220.

Meyer, L.O., Schulte, K., Grove-Nielsen, E., 2007. Optimisation of a pyrolysis process for recycling CFRP, in: Proceedings of 16th International Conference on Composite Materials. Kyoto.

Meyer, L.O., Schulte, K., Grove-Nielsen, E., 2009. CFRP-Recycling following a pyrolysis route: Process optimization and potentials. Journal of Composite Materials. 43(9), 1121-1132.

Milberg, E., 2017, CRTC produces first-ever automotive seatback using recycled carbon fiber from ELG, http://compositesmanufacturingmagazine.com/2017/09/crtc-produces-first-ever-automotive-seatback-using-recycled-carbon-fiber/ (Accessed 13/Jun, 2019)

Miyake, T., Imaeda, S., 2016. A dry aligning method of discontinuous carbon fibers and improvement of mechanical properties of discontinuous fiber composites. Advanced Manufacturing: Polymer & Composites Science. 2(3-4), 117-123.

Montoya, J., Chejne Janna, F., Garcia-Perez, M., 2015. Fast pyrolysis of biomass: a review of relevant aspects. Part I: Parametric study, Dyna. 82(192), 239-248

Nicolais, L., Pisanova, E., 2012. Recycling of carbon fiber composites. In Wiley Encyclopedia of Composites, L. Nicolais (Ed.). doi:10.1002/9781118097298.weoc213

Onwudili, J., Miskolczi, N, Nagy, T, Lipóczi, G., 2016. Recovery of glass fibre and carbon fibres from reinforced thermosets by batch pyrolysis and investigation of fibre re-using as reinforcement in LDPE matrix. Composites Part B: Engineering, 91, 154-161

Song, C., et al., Recycling carbon fiber from composite waste and its reinforcing effect on polyvinylidene fluoride composite: Mechanical, morphology, and interface properties. Polymer Composites, 2017. 38(11): p. 2544-2552.

Pang, E.J.X., Pickering, S.J., Chan, A., Wong, K.H., Lau, P.L., 2012. N-type thermoelectric recycled carbon fibre sheet with electrochemically deposited Bi2Te3. Journal of Solid State Chemistry. 193, 147-153.

Pickering, S.J., 2006. Recycling technologies for thermoset composite materials—current status. Compos Part A: Appl Sci Manuf. 37 (8), 1206-1215.

Pickering, S.J., Turner, T.A., Meng, F., Morris, C.N., Heil, J.P., Wong, K.H., Melendi, S., 2015. Developments in the fluidised bed process for fibre recovery from thermoset composites, in: 2nd Annual Composites and Advanced Materials Expo, CAMX 2015, Dallas, Texas.

Pimenta, S. & Pinho, S.T., 2011. Recycling carbon fibre reinforced polymers for structural applications: technology review and market outlook. Waste Manag. 31(2), 378–392.

Pütün, E., Uzun, B.B., Pütün, A.E., 2006. Production of bio-fuels from cottonseed cake by catalytic pyrolysis under steam atmosphere. Biomass and Bioenergy. 30(6), 592-598.

Ravindran, A.R., Ladani, R.B., Wu, S., Kinloch, A.J., Wang, C.H., Mouritz, A.P., 2018. The electric field alignment of short carbon fibres to enhance the toughness of epoxy composites. Compos Part A: Appl Sci Manuf. 106, 11-23.

Rybicka, J., Tiwari, A., Leeke, G.A., 2016. Technology readiness level assessment of composites recycling technologies. J. Clean Prod. 112, 1001-1012.

Septien, S., Escudero Sanz, F.J., Salvador, S., Valin, S., 2018. The effect of pyrolysis heating rate on the steam gasification reactivity of char from woodchips, Energy. 142, 68-78.

Shuaib, N. A., Mativenga, P. T., Kazie, J., Job, S., 2015. Resource efficiency and composite waste in UK supply chain. Procedia CIRP, 29, 662–667.

Söderholm, P., Tilton, J.E., 2012. Material efficiency: An economic perspective. Resources, Conservation and Recycling. 61, 75-82.

Sokoli. H.U., Simonsen, M.E., Søgaard, E.G., 2018. Towards understanding the breakdown and mechanisms of glass fiber reinforced polyester composites in sub-critical water using some of the most employed and efficient additives from literature. Polym Degrad Stab, 152. 10–19.

Song, C., Wang, F., Liu, Y., Wang, X., Yang, B., 2017. Recycling carbon fiber from composite waste and its reinforcing effect on polyvinylidene fluoride composite: Mechanical, morphology, and interface properties. Polymer Composites, 38(11), 2544-2552.

Stahel, W.R., 2013. Policy for material efficiency—sustainable taxation as a departure from the throwaway society. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 371 (1986), 20110567.

Suzuki, T., Takahashi, J., 2005. Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger carsm in: Ninth Japan International SAMPE Symposium JISSE-9. Tokyo, Japan, pp. 14-19.

Thomas, C., Borges, P.H.R., Panzera, T.H., Cimentada, A., Lombillo, I., 2014. Epoxy composites containing CFRP powder wastes. Compos. B Eng. 59, 260-268.

Tse, T., Esposito, M., Soufani, K., 2015. Why the circular economy matters. European Business Review. 11, 59-63.

UNEP, 2006. Circular Economy: An Alternative for Economic Development. UNEP DTIE, Paris.

Unsworth, J.F., Barratt, D.J., & Roberts, P.T., 1991. Coal quality and combustion performance: an international perspective. Coal Science and Technology. 19, 1-609.

Uzun, B.B., Pütün, A.E., Pütün, E., 2007. Rapid pyrolysis of olive residue. 1. Effect of heat and mass transfer limitations on product yields and bio-oil compositions. Energy & Fuels. 21(3), 1768-1776.

van de Werken, N., Reese, M.S., Taha, M.R., Tehrani, M., 2019. Investigating the effects of fiber surface treatment and alignment on mechanical properties of recycled carbon fiber composites. Compos Part A: Appl Sci Manuf. 119, 38-47.

Veers, P.S., Ashwill, T.D., Sutherland, H.J., Laird, D.L., Lobitz, D.W., Griffin, D.A., Mandell, J.F., Musial, W.D., Jackson, K., Zuteck, M. and Miravete, A., 2003. Trends in the design, manufacture and evaluation of wind turbine blades. Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology. 6(3), 245-259.

Vo Dong, P.A., Azzaro-Pantel, C., Cadene, A.-L., 2018. Economic and environmental assessment of recovery and disposal pathways for CFRP waste management. Resources, Conservation and Recycling. 133, 63-75.

Wang, B., Xu, F., Zong, P., Zhang, J., Tian, Y.,Qiao, Y., 2019. Effects of heating rate on fast pyrolysis behavior and product distribution of Jerusalem artichoke stalk by using TG-FTIR and Py-GC/MS. Renewable Energy, 132, 486-496.

Wang, P., Kuah, A.T.H. (2018) Green marketing cradle-to-cradle: remanufactured products in Asian markets. Thunderbird International Business Review. 60 (5), 783-795.

Witik, R.A., Teuscher, R., Michaud, V., Ludwig, C., Månson, J.-A.E., 2013. Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling. Compos Part A: Appl Sci Manuf. 49, 89-99.

Wölling, J., Schmieg, M., Manis, F., Drechsler, K., 2017. Nonwovens from recycled carbon fibres – comparison of processing technologies. Procedia CIRP. 66, 271-276.

Wong, K., Rudd, C., Pickering, S., Liu, X., 2017. Composites recycling solutions for the aviation industry. Science China Technological Sciences. 60(9), 1291-1300.

Wong, K.H., Pickering, S.J., Rudd, C.D., 2010. Recycled carbon fibre reinforced polymer composite for electromagnetic interference shielding. Compos Part A: Appl Sci Manuf. 41(6), 693-702.

Wong, K.H., Syed Mohammed, D., Pickering, S.J., Brooks, R., 2012. Effect of coupling agents on reinforcing potential of recycled carbon fibre for polypropylene composite. Composites Science and Technology. 72(7), 835-844.

Wong, K.H., Turner, T.A., Pickering, S.J., Warrior, N.A., 2009. The potential for fibre alignment in the manufacture of polymer composites from recycled carbon fibre. SAE International Journal of Aerospace. 2(2009-01-3237), 225-231.

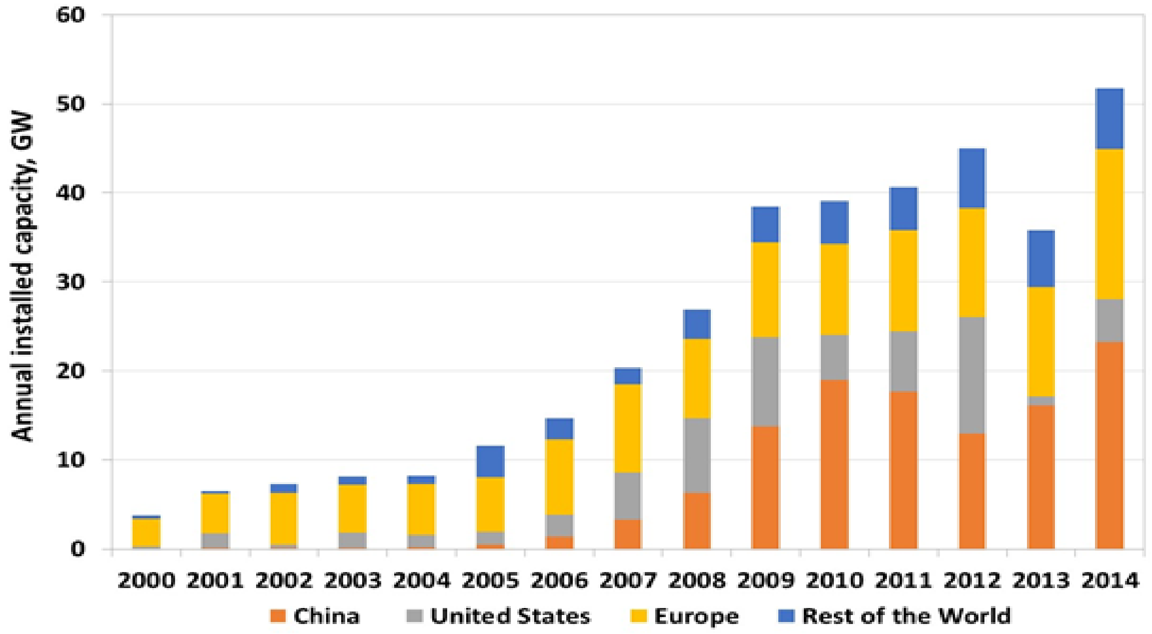
Wood, K., 2010. Carbon fiber reclamation: going commercial. High Performance Composite. 3, 1-2.

Yang, J., Liu, J., Liu, W., Wang, J., Tang, T., 2015, Recycling of carbon fibre reinforced epoxy resin composites under various oxygen concentrations in nitrogen–oxygen atmosphere, Journal of Analytical and Applied Pyrolysis, 112, 253-261

Zazulia, N., 2018, Boeing partners with ELG Carbon Fibre on composite recycling, https://www.aviationtoday.com/2018/12/05/boeing-partners-elg-carbon-fibre-composite-recycling/ (Accessed 13/Jun/2019).

A circular economy approach to green energy: Wind turbine, waste, and material recovery

Figure 1: Annual new wind turbine installations by region



Source: Adapted from Liu and Barlow (2017)

Figure 2. Thermal treatment profile used in TGA test

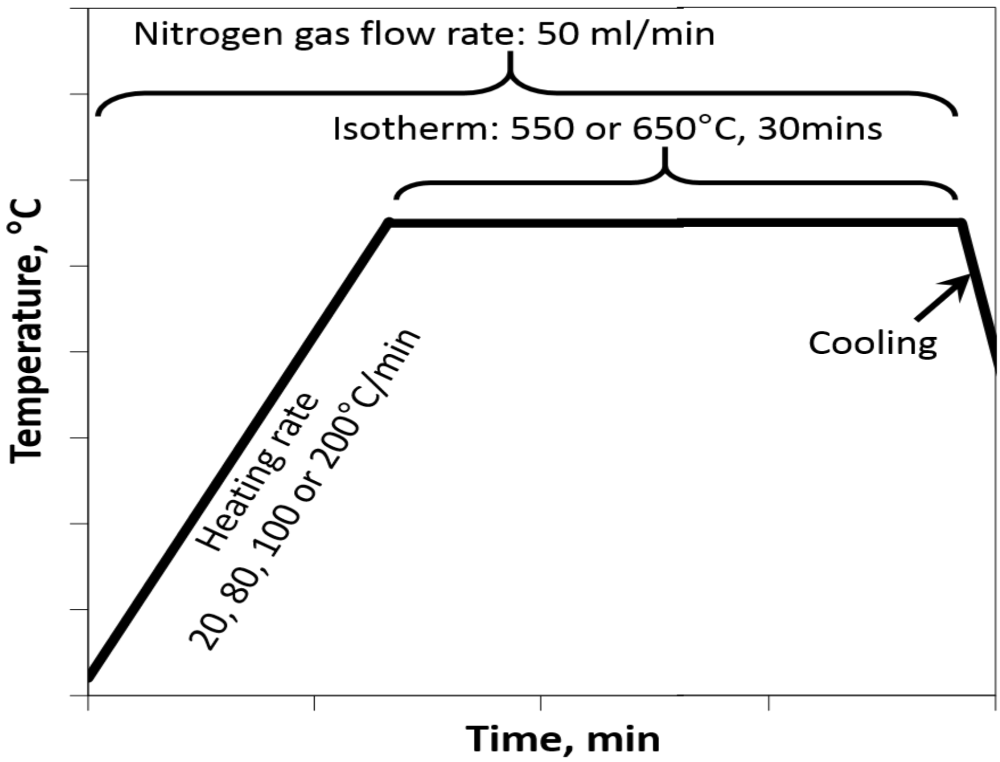


Figure 3. Effect of heating rates and pyrolysis temperatures on CFRP's TG curves

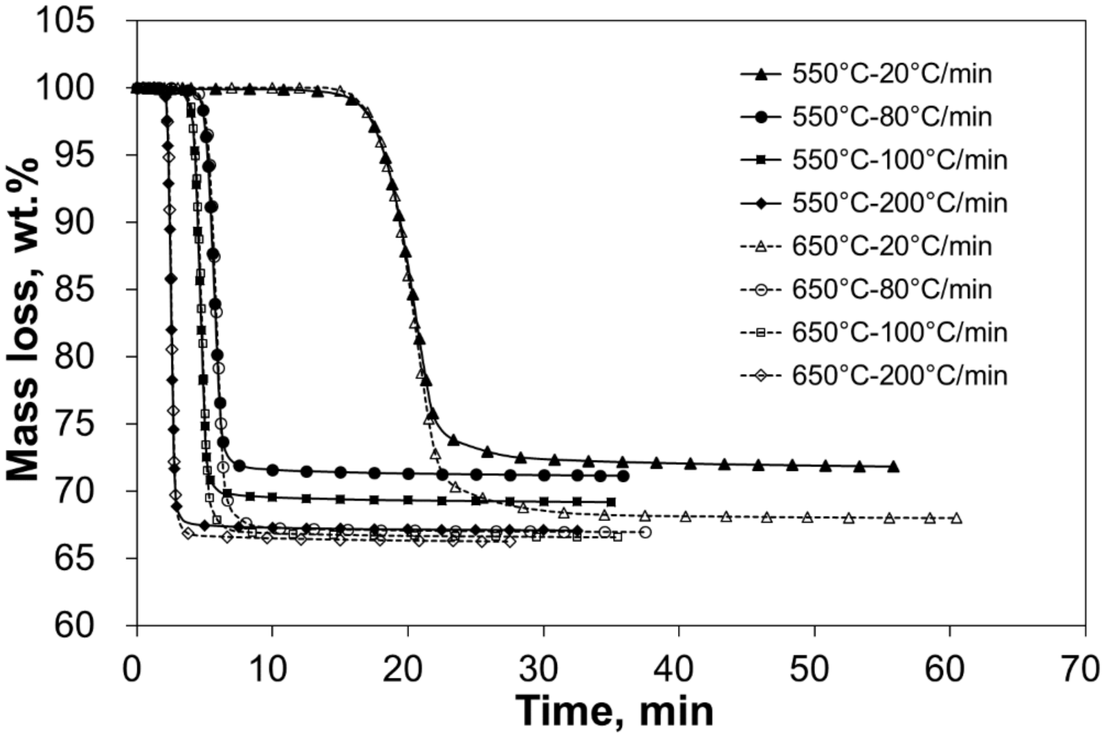


Figure 4: Effect of heating rates and pyrolysis temperatures on CFRP's mass loss

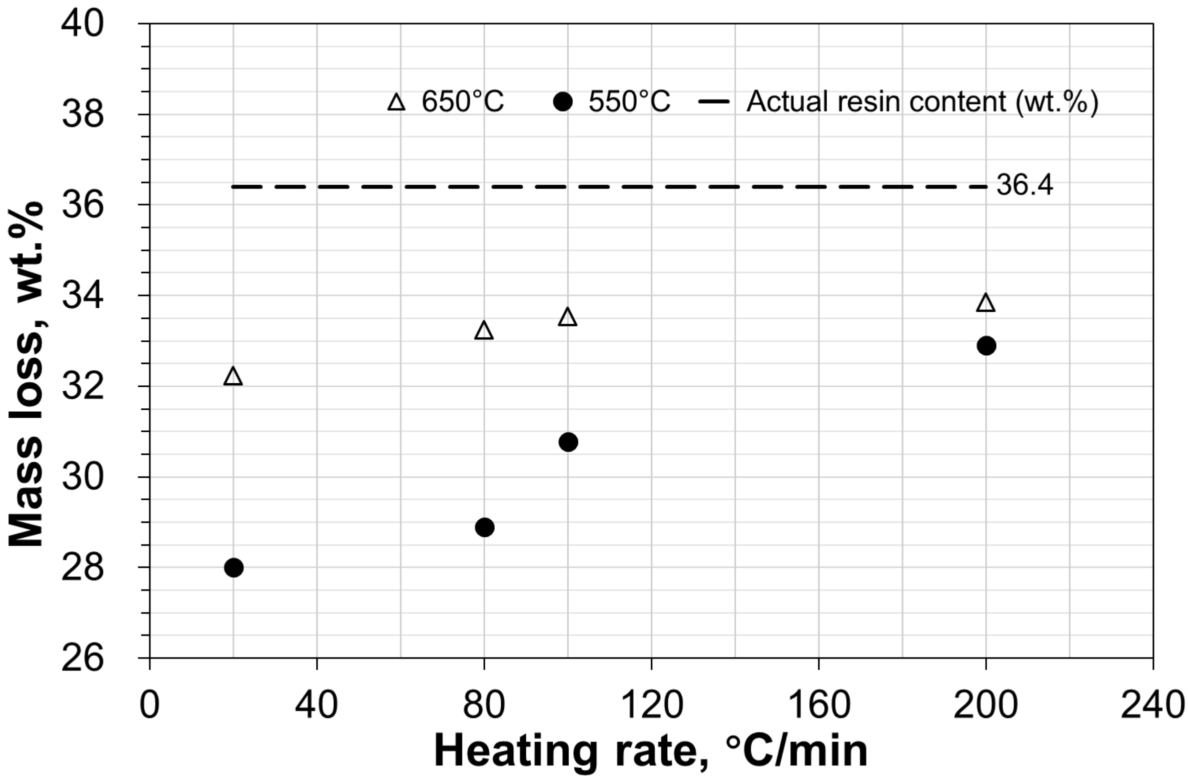


Figure 5. Effect of nitrogen gas flowrate s on CFRP's mass loss with (a) 550°C and (b) 650°C pyrolysis temperature

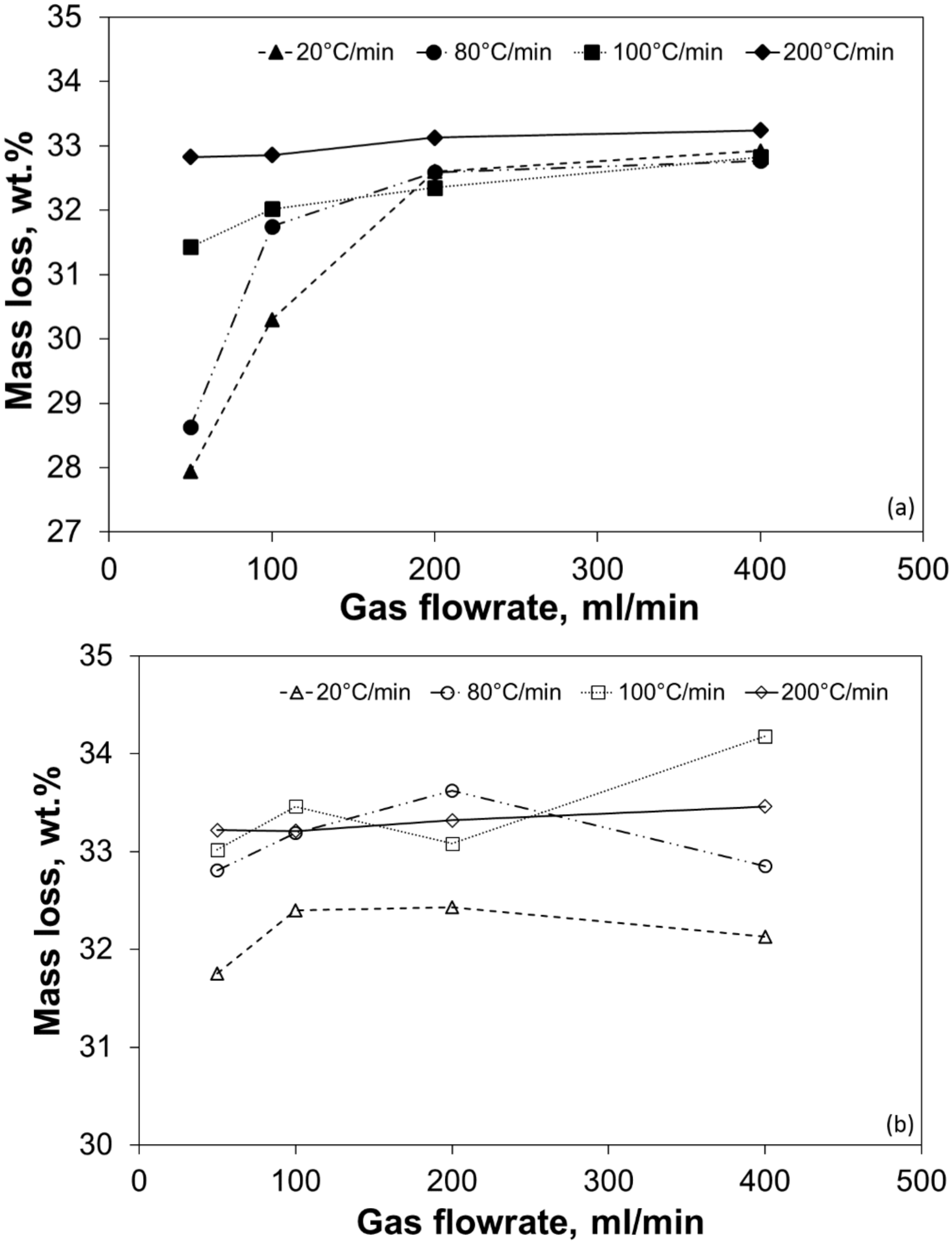


Figure 6. Effect of heating rates on intrinsic reactivity of char generated at 550 and 650 ºC.

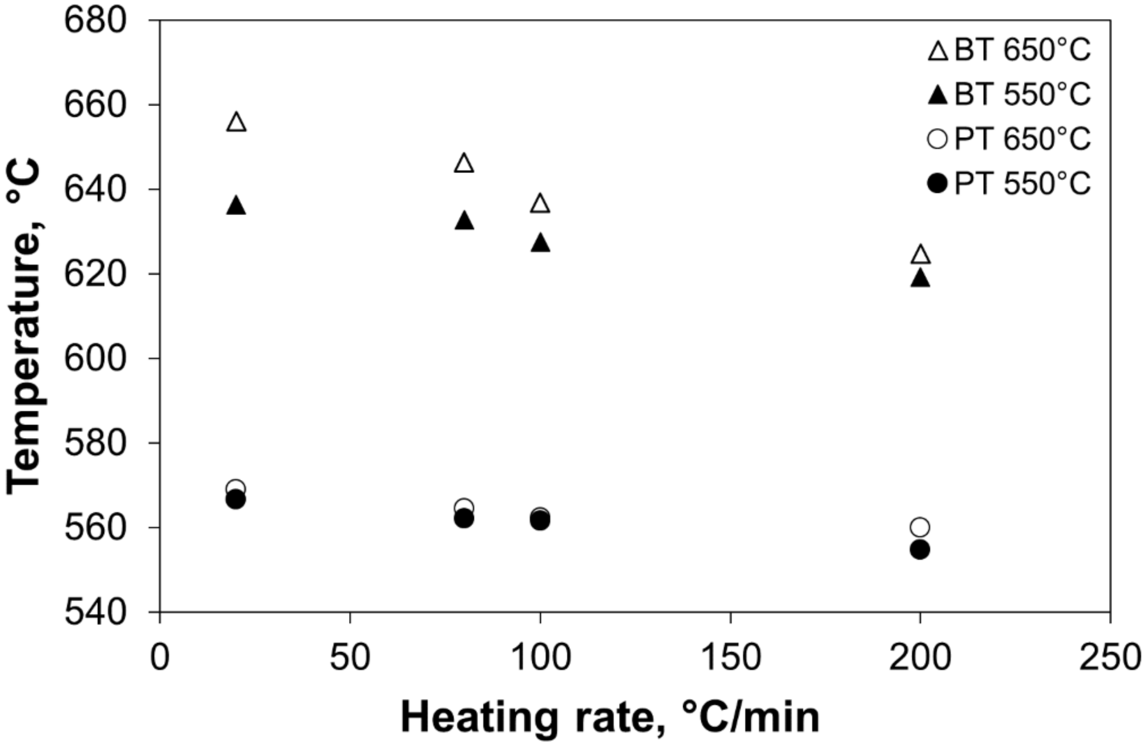


Figure 7. SEM images of pyrolytic chars produced at different temperatures and heating rates (a) 550°C, 20°C/min (b) 650°C, 20°C/min (c) 550°C, 200°C/min and (d) 650°C, 200°C/min

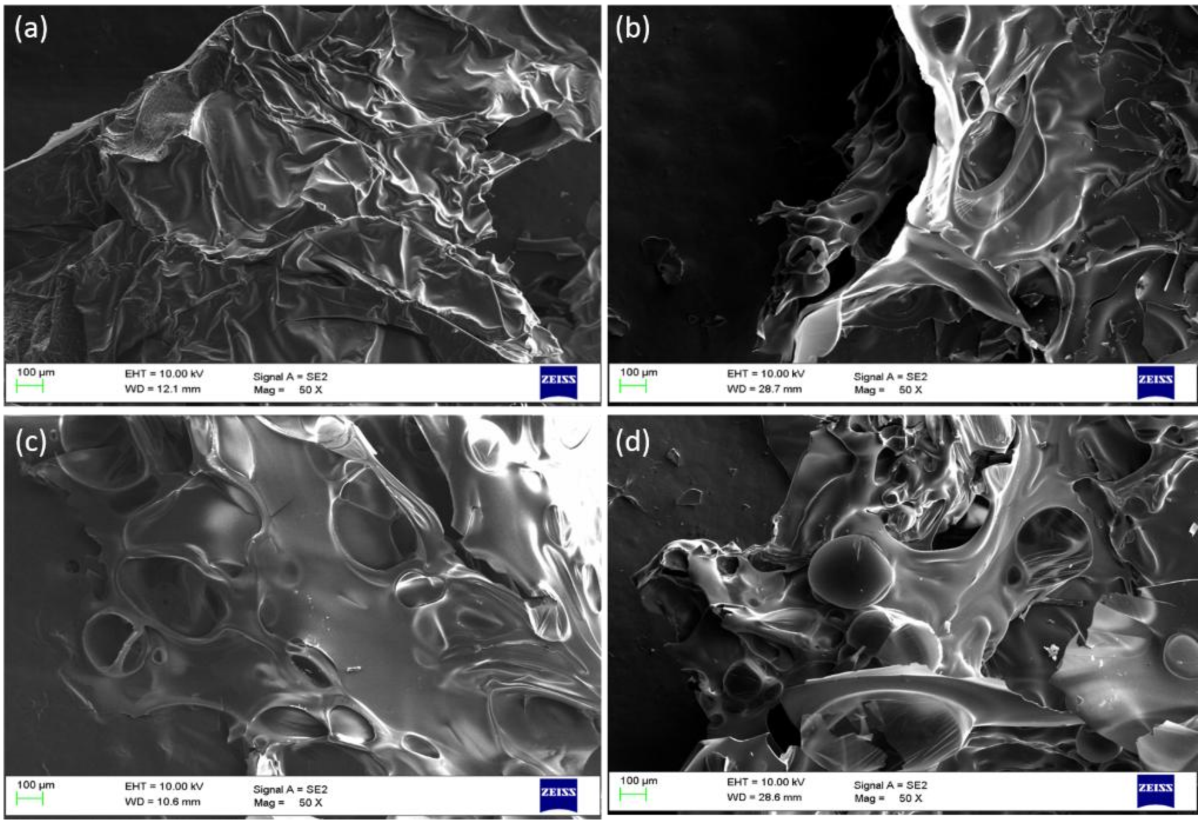


Figure 8. Circular economy for end-of-life wind turbine blades