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Wind Turbine Blade End-of-Life Options: An Economic Comparison

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Abstract

Global wind energy is developing rapidly, with total installed capacity having increased from 24,332 MW in 2001 to 650,758 MW in 2019. Environmental concerns have been raised over the large volumes of waste that will be generated as these wind turbine blades are decommissioned over the coming decades. Although wind turbines are largely clean during operation, in manufacture and end-of-life stages they release emissions and consume significant energy. Wind turbine blades are mainly made from lightweight thermoset composites (glass fibre/carbon fibre), which are economically challenging to recycle. This study aims to understand the economic feasibilities of recycling technology options for blade waste management. We have used a quantitative method, first building a financial performance model for wind turbine blade end of life, then evaluating and comparing the financial performance for all available end of life options, and finally performing a sensitivity analysis. We found that mechanical recycling and fluidised-bed recycling are the optimal options of the ready-to-go technologies, and chemical recycling is the optimal option for technologies currently available only at lab scale.

Key Words: Wind energy; Composites recycling; End-of-life wind turbine blades; Wind energy economy

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1 Introduction

Wind energy is one of the most promising sources of clean energy to mitigate further global warming caused by burning fossil fuels. Global wind energy has developed rapidly over the last two decades, from 24.33 GW installed capacity in 2001 to 650.76 GW in 2019 with a 20% compound annual growth rate. Wind turbines are a clean technology if only the operational stage of their life cycle is considered. However, the manufacture and end-of-life (EoL) stages require large amounts of energy and release significant pollutions including greenhouse gases (GHGs) (Morini et al., 2021).

Wind turbine blades are mainly made with composite materials comprising thermosetting resin and glass fibre (GF) or carbon fibre (CF). They are lightweight with a cross-linked matrix material structure resulting in high fatigue resistance and mechanical strength. However, this structure makes them difficult to recycle (Karuppannan Gopalraj and Kärki, 2020; Krauklis et al., 2021; Pickering, 2006). Following 9-27 year service periods wind turbines are decommissioned, generating large volumes of blade waste (Cooperman et al., 2021; Lichtenegger et al., 2020; Liu and Barlow, 2017; Sommer et al., 2020). It is estimated that 789,000 tonnes of composite waste will be generated in 2021 and a total of 43 million tonnes by 2050, raising environmental concerns and heightening the urgency to provide composite waste management options (Liu and Barlow, 2017) in our previous paper. We also projected that the EoL blade wastes will become a critical global challenge by 2028.

Most blade waste to date has been sent to landfill (Pickering, 2006), a disposal route which will not be cheap/legal in the future as environmental legislation becomes increasingly restrictive for solid waste (Sadeghi Ahangar et al., 2021; Tsai et al., 2021; Tseng et al., 2021). For example, many countries have introduced landfill gate fees/taxes to drive a shift towards recycling. In the UK, the median landfill gate fee is £113/tonne including a landfill tax of £89/tonne (WRAP (Waste & Resources Action Programme), 2019).

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Composite waste can be recycled via mechanical recycling, thermal recycling (e.g., pyrolysis and fluidised bed processes) or chemical recycling (Krauklis et al., 2021; Meng et al., 2018b; Rani et al., 2021; Zhang et al., 2020). Mechanical recycling in this context normally involves grinding the composite to produce particles typically between 50μm and 10mm which can be incorporated into the manufacture of new composites as fillers (Pickering, 2006). The degradation in mechanical properties means that applications of such recyclate are low-value (Li et al., 2016). Pyrolysis is available as a commercially established operation (e.g., ELG Carbon Fibre Ltd. in the UK with a recycling capacity of 2,000 t/yr (ELG Carbon Fibre Ltd, 2021)). In this process, the resin is thermally decomposed into hydrocarbon products, allowing recovery of the carbon fibres. Similarly, the fluidised bed recycling process oxidises the polymer matrix to enable carbon fibre recovery (Meng et al., 2017; Pickering, 2006), and can be used to treat mixed and/or contaminated end-of-life composite waste. Solvolysis uses solvents (water, alcohol and/or acid) to break bonds in the resin matrix to produce lower molecular weight chemicals, allowing recovery of the fibres at lower temperature than thermal processes, though often at higher pressure (Keith et al., 2016; Mattsson et al., 2020).

The environmental and financial benefits of recycling are dependent on the waste type and the EoL processes used. If some of the recovered fibres and matrix-derived chemicals can be re-used as a substitute for virgin materials then there can be reduction in the overall environmental impact (Heng et al., 2021; Liu et al., 2019). For recycling to be financially beneficial, the EoL costs must be offset against the value of the recyclates (Gopalraj and Kärki, 2020; Meng et al., 2018a) . A comparative study of costs for existing recycling technologies for both GF and CF composites waste is missing.

In this paper, we aim to compare the economic performance of different recycling technologies for blade waste management. We discuss the methodology of cost analysis including the calculation logic and parameter settings of the process-based cost model (Bloch and Ranganthan, 1991). In the EoL processes, each blade is disassembled, and the waste is classified. Blade materials fall into three categories: 100% glass fibre (GFRP), 100% carbon fibre (CFRP) and a mixture of the two (hybrid). The analysis is simplified by analysing the GFRP and CFRP fractions of the hybrid separately and combining in the appropriate proportions for the blade type. Therefore, we analyse the financial performance of the EoL options by considering material type (GF and CF) but not specific blade models. A cost analysis is performed for GF and CF respectively considering the recycling cost and recyclate value of each fibre EoL option. Differing from previous studies, this paper provides a transparent and comparative economic assessment of different GFRP and CFRP blade waste recycling paths based on literature data and process models of lab process or pilot plant. The underlying data is provided and includes details of different recycling technologies. There is a lack of publicly available cost information regarding the performance of commercial-scale/pilot-scale composite recovery facilities. The results can inform better decision-making among all available recycling methods based on the commercial value of recycling options for both GF and CF when facing carbon tax and stricter regulations.

2 Methodology

The wind turbine blade recycling process consists of four steps:

1) dismantling the wind turbine
2) disassembling and cutting the wind turbine blades into metre-sized or smaller scrap convenient for transportation
3) transporting the scrap to the recycling centre
4) recycling the scrap

In this study, we are looking only to recycle and produce the recyclate as including steps 2-4. Step 4 covers costs associated with the recycling or other end-of-life process (such as landfill) and includes revenue from recyclates (fibre, filler, resin and energy). The net cost (C_{net}) can therefore be written as:

$$C_{net} = \sum \left(C_{disassembling} + C_{transport} + C_{recycling} \right) - \sum \left(I_{fibre} + I_{filler} + I_{resin} + I_{energy} \right)$$

Where $C_{dissembling}$ is the dissembling process cost at step 2, $C_{transport}$, is the transportation cost at step 3, $C_{recycling}$ is the recycling process cost at step 4, I_{fibre} is the revenue from fibre recyclate, I_{filler} is the revenue from filler recyclate, and I_{resin} is the revenue from resin recyclate and I_{energy} is the revenue from energy recovery.

For each EoL option, the recycling process is briefly described and then the recycling cost and recyclate value are discussed. The cost data of landfill and incineration are obtained from industrial partners and literature review. For other EoL options, there is no publicly available cost data and thus they are estimated from the cost models using best available data from literature and industrial partners. All cost data taken from the United States, the United Kingdom, Europe, and China markets is converted into the United States dollar (USD) (The World Bank, 2020). Costs are then extrapolated to those of year 2019 based on the Chemical Engineering Plant Cost Index (Chemical Engineering, 2020). Wind turbine blade EoL waste processing routes are presented in Figure 1.

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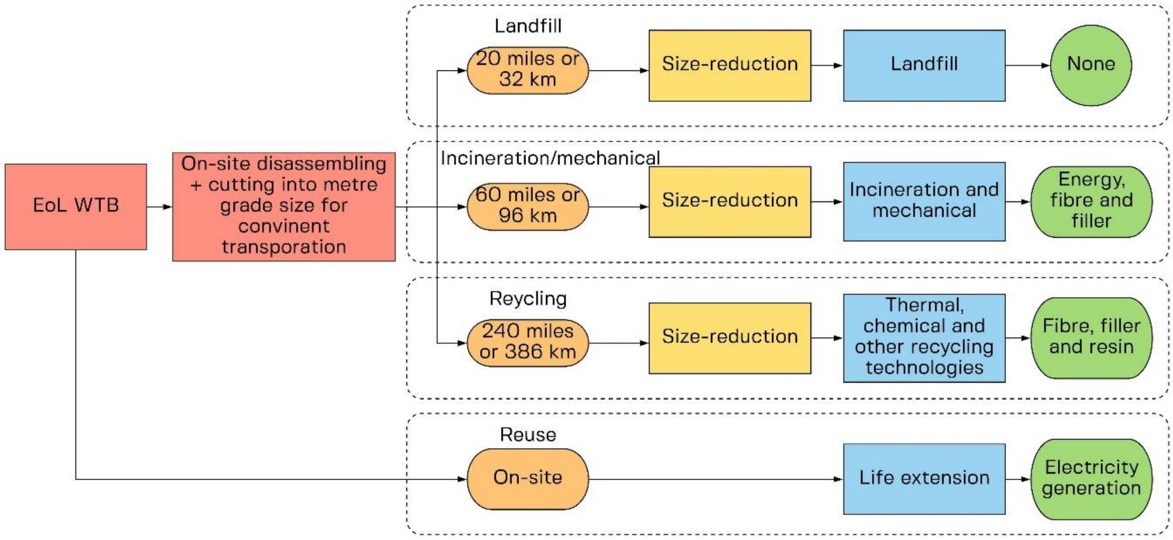

Figure 1: EoL wind turbine blade waste processing flow with transportation distance and outputs.

The incomes from virgin material value and recyclate value have been calculated based on assumptions described in Section 2.1. The disassembly and cutting (step 2) cost are stated in Section 2.2. The transportation (step 3) cost is stated Section 2.3. The recycling cost and recyclate value (step 4) are calculated in Section 2.4.

2.1 Material value

Most recyclate from the recycling processes is degraded to different degrees. As tensile strength is one of the most important factors in selecting material for wind turbine blades (Dvorak, 2010), we assume that the reduction in fibrous recyclate value is proportional to its loss of tensile strength. We then calculate the recyclate values based on the referenced virgin material as in Table S1.

The key assumptions regarding recyclate value are as follows:

For the material value

- The value of the recycled fibre is assumed to be proportional to its tensile strength. If the strength of the recycled fibre is 80% of virgin fibre, then its value is 80% of virgin fibre.
- All EoL options require the blade to be reduced in size during or before the recycling processes. All the recyclate has been cut or shredded. Therefore, all the recycled fibre is short fibre, and thus the recycled fibre value is calculated based on virgin short fibre.
- The value of recycled filler is the same as that of virgin filler.
- The value of recycled resin is 50% of that of virgin resin (Oliveux et al., 2015).

2.2 Cutting and disassembly cost

The cutting and disassembly cost for composite waste is \$10 to \$70 per tonne, varying between regions (Hedlund-åström, 2005; Liu and Barlow, 2015). An average value of \$40/t is used in the base case.

2.3 Transportation cost

The method of transportation is one of the major factors affecting the logistics cost and depends on the waste location. Onshore wind turbine blades are typically transported by both road and sea freight. Offshore blades are primarily transported by sea freight. However offshore cases are excluded in this study as explained in section 1.2 in SI.

Due to the large blade size, onshore blades are transported by expensive heavy-duty trucks during the installation phase. In the EoL stage, the blade needs to be cut into small pieces fitting light-duty trucks in order to reduce the logistics cost (Liu, 2015). The logistics cost has been calculated in various scenarios as presented in section 1.2 in SI. The key results are presented in FigureS3, making the comparison between practices in UK and China.

2.4 Waste EoL options

We consider nine approaches to handle the wind turbine blade waste for both glass fibre and carbon fibre wastes, of which two (Landfilling and Life extension (LE) 5 years) do not involve recycling. Incineration, Mechanical recycling and Pyrolysis use established technologies and are ready-to-go. The other recycling technologies considered (Fluidised bed, High voltage fragmentation (HVF), Microwave assisted pyrolysis (MAP) and Chemical recycling) are still regarded as in the development phase and are not yet available at commercial scale. The model has been summarised in Tables 1 and 2 and further details can be found in Section 1.2 in SI. For the recycling process

- Wind turbine blades are made of two major materials: fibre and resin. Other parts of the structure include copper lightning protectors, steel root secure bolts and the sandwich core material (which may be made from balsa or polymer foam). Those supporting components are less than 5 wt% for most blade models and will be removed during EoL pre-processing (Sinomatech Wind Power Blades, 2014). Hence the waste feedstock is assumed to be 60 wt% fibre and 40 wt% resin.
- The recycling cost for each process and cost for landfill and incineration are described in section 1.2 in the supporting information.
- The total recyclate value = energy output from process * electricity cost + ((fibre yield rate * fibre performance * virgin fibre cost + filler yield rate * filler cost) * fibre weight fraction in feedstock (60%) + (resin yield rate * resin performance * virgin resin cost) * resin weight fraction (40%)) * (100%-overall process loss (5%))
- The yield rates and recyclate performance depend on recycling technologies.

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Table 1: GF recyclate value

Glass fibre														
	Fibre yield rate	Virgin fibre value per t	% virgin performance conserved in recyclate	Filler yield rate	Virgin filler value per tonne	% virgin performance conserved in recyclate	Feedstock fibre content	Resin yield rate	Virgin resin value per tonne	% virgin performance conserved in recyclate	Feedstock resin content	Overall process yield	Years extended	Recyclate value/ $ per tonne
Landfill	Nothing													$0.0
Incineration	Energy recovered only		-	-	-	-	-	-	-	-	-	-		$58.7
Mechanical	58.3%[1]	$1,300.0	78.0%[1]	41.7%	$310.00	100.0%	60%	0%	$0.0	0%	40%	95%		$410.6
Fluidised-Bed	44.0%[2]	$1,300.0	50.0%[2]	7.6%	$310.0	100.0%	60%	0%	$0.0	0%	40%	95%		$176.4
Pyrolysis	56.0%[3]	$1,300.0	52.0%[3]	14.0%	$310.0	100.0%	60%	0%	$0.0	0%	40%	95%		$240.5
MAP	56.0%[4]	$1,300.0	52.0%[4]	14.0%	$310.0	100.0%	60%	0%	$0.0	0%	40%	95%		$240.5
Chemical	100.0%[5]	$1,300.0	58.0%[5]	0.0%	$310.0	100.0%	60%	100%	$5,571.0	50%	40%	95%		$1,488.3
HVF	90.0%[6]	$1,300.0	88.0%[6]	0.0%	$310.0	100.0%	60%	0%	$0.00	0%	40%	95%		$586.9
Life extension 5 years	-	$1,641.8	-	-	-	-	60%	-	$5,571.0	-	40%	-	5	$803.4

References:

1 (Palmer et al., 2009), 2 (Pickering et al., 2000b), 3 (Cunliffe et al., 2003), 4 assumption made in this study, 5 (Keith et al., 2016), 6 (Rouholamin et al., 2014)

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Table 2: CF recyclate value

Carbon fibre														
	Fibre yield rate	Virgin fibre value per tonne	% virgin performance conserved in recyclate	Filler yield rate	Virgin filler value per t	% virgin performance conserved in recyclate	Feedstock fibre content	Resin yield rate	Virgin resin value per tonne	% virgin performance conserved in recyclate	Feedstock resin content	Overall process yield	Years extended	Recyclate value/ $ per tonne
Landfill	Nothing													$0.0
Incineration	Energy recovered only		-	-	-	-	-	-	-	-	-	-		$58.7
Mechanical	0.0%	$0.0	0.0%[1]	100.0%	$5,553.48	100.0%	60%	0%	$0.0	0%	40%	95%		$3,165.5
Fluidised-Bed	60.0%	$23,636.4	75.0%[2]	7.6%	$5,553.48	100.0%	60%	0%	$0.0	0%	40%	95%		$6,303.3
Pyrolysis	56.0%	$23,636.4	80.0%[3]	14.0%	$5,553.48	100.0%	60%	0%	$0.0	0%	40%	95%		$6,478.9
MAP	56.0%	$23,636.4	80.0%[4]	14.0%	$5,553.48	100.0%	60%	0%	$0.0	0%	40%	95%		$6,478.9
Chemical	100.0%	$23,636.4	96.0%[5]	0.0%	$5,553.48	100.0%	60%	100%	$5,571.0	50%	40%	95%		$13,992.3
HVF	90.0%	$23,636.4	83.0%[6]	0.0%	$5,553.48	100.0%	60%	0%	$0.00	0%	40%	95%		$10,064.1
Life extension 5 years	-	$29,850.7	-	-	$5,553.48	-	60%	-	$5,571.0	-	40%	-	5	$5,034.7

References: 1 assumption made in this study, 2 (Meng et al., 2017), 3 (Meyer et al., 2009; Onwudili et al., 2013), 4 assumption made in this study, 5 (Bai et al., 2010; Hyde et al., 2006; Jiang et al., 2009; Liu et al., 2004; Liu et al., 2009; Okajima et al., 2009; Okajima et al., 2012; Piñero-Hernanz et al., 2008), 6 (Weh, 2012)

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3 Results and discussion

In this section we analyse the current financial viability of different EoL options for GF and CF wind turbine blade waste. Sensitivity analysis is used to predict how comparative costs may change for the future, so indicating which processes may become favourable as recycling technologies and infrastructure evolve.

3.1 Comparative costs for EoL processes

3.1.1 Glass fibre waste

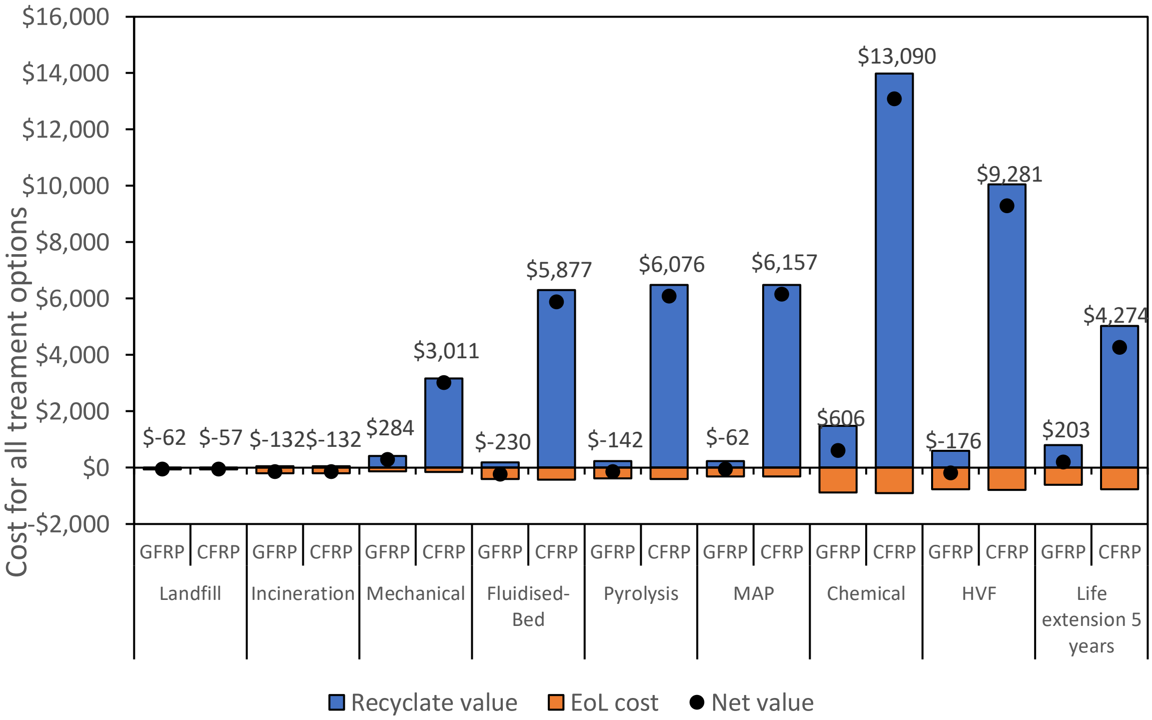

Figure 2: Comparison of cost, recyclate value and net profit for EoL options for GFRP and CFRP waste from wind turbine blades.

The total recycling costs, recyclate values and net profits of each glass fibre EoL option are summarised in Figure 2. This overview illustrates our key findings: three EoL options make a profit (i.e., mechanical and chemical recycling, and LE 5 years) and the remaining six are in deficit.

For the conventional waste processes, the EoL costs of landfill and incineration are around the same. Since the incineration process can recover energy equivalent to $59 per tonne waste, this makes the net cost of incineration lower than landfill.

Of the ready-to-go recycling options, mechanical recycling is the only one to create profit. The cost of mechanical recycling is very low compared to other recycling processes as this process is less complex. For pyrolysis, a thermal process, the energy consumption is high, and more equipment is necessary. The yield and performance of the fibrous product recovered by the thermal processes are also lower than those of mechanical recycling. Hence recycling GF blade waste using pyrolysis is unlikely to be profitable, with projected losses standing at over $140 per tonne.

Of the lab-scale technologies (fluidised bed, MAP, chemical recycling and HVF) chemical recycling is by far the most profitable of all EoL options. The extra high value resin recovered from chemical recycling makes a high recyclate value which can outweigh its high recycling equipment cost. It should be noted that the yield rate of 100% in the assumption is based on the lab scale and it may vary when the process scales up, affecting recyclate value. The resin value is also optimistically assumed to be 50% that of new resin although this has not been reported in the literature. All these uncertainties need to be further addressed in future research. Microwave assisted pyrolysis (MAP) requires only a quarter of the recycling energy of conventional pyrolysis (Shuaib and Mativenga, 2016). This advantage significantly cuts down the recycling cost of MAP and reduces its net cost to $61.7/t. This figure is the closest to the cost breakeven within all options but leading to a small loss. Given improved recyclate performance or yield rate the recyclate value can increase making MAP financially viable to operate without subsidy. In contrast, high voltage fragmentation (HVF) shows negative profits mainly due to its high energy consumption along with high equipment costs. The glass fibre recovered from HVF, however, is considerably stronger than the fibre recovered by the thermal and chemical treatments (88% of virgin strength compared to around 50%) (Liu et al., 2019). Therefore, if the HVF process is developed and scaled up, leading to reduced costs, then it may become a financially viable option in the future.

The LE plan is profitable with a margin of $202.9/t, just lower than that of mechanical recycling. The drawbacks to LE are the repair service reliability and the willingness of wind farm owners to extend the lifetime of blades. As with other products, more problems may occur towards the end-of-life of blades and these are unavoidable. The function of a wind turbine is the generation of electricity which, in turn, makes profits for the wind farm. Possible high failure rates may lead to both extra repair costs and losses in electricity sales whilst awaiting repair. Furthermore, when repair is not possible then damaged blades must be replaced, which can take up to a few months and makes the life extension option a net economic loss. Some blade manufacturers and third-party service providers (Power, 2015; Tecnológica, 2015) have started offering a life extension programme to their customers (Siemens Gamesa, 2021) using service standards launched in March 2016 (DNV GL, 2016), but this is still in its early stages. Furthermore, there is another potential barrier: the willingness of wind farm owners to join the scheme. New blades have a higher aerodynamic efficiency than older blades made 20 years ago, which can improve the annual electricity production (AEP) by 2-4% leading to a higher income (Siemens AG, 2014). In addition, blade capital cost is quite low compared to the value of the extra electricity generated so the cost of a new blade can be paid back in a short period. In sum, these reasons may encourage wind farm owners to opt for new blades rather than extend the lifetime of existing blades. It also reveals that the EoL options should not simply be considered in terms of the recycling processing costs and recyclate value alone. Other factors such as the willingness of stakeholders to participate should also be considered in future work.

3.1.2 Carbon fibre waste

Cost for CF waste EoL options presents a different result from GF. This is primarily due to the high value of CF, which has the effect of reducing the impact of recycling cost and shifting the dominant factors to recyclate value. Therefore, the EoL options that result in high recyclate performance and have a high yield rate are significantly more profitable.

As shown in Figure 2, none of the CF EoL options, landfill and incineration alone are profitable at all as they discard the high value CF content, while all the other options are profitable. Among the ready-to-go technologies, the net profit of mechanical recycling is the lowest, 50% less than for pyrolysis, the other ready-to-go technology. This is because the recyclate value is lower (fillers only for mechanical recycling compared to fibres with a retained strength of around 80% for pyrolysis). Pyrolysis therefore appears to be a promising recycling process for industrial implementation.

Looking at the lab-scale technologies, the retained strength of the fibres from the fluidised bed process is comparable to pyrolysis at 80%, and the cost of the process is also similar. Future viability of this process depends on how it develops during scale-up development. The net profit of MAP is similar to that of pyrolysis but significantly lower than that of chemical recycling and HVF. Chemical recycling performs the best mainly due to the minimal performance loss of the recycled fibre and its capability of recovering resin content. HVF's position regarding CF is completely different to its position for GF waste (-$176/t, the third highest loss). The recyclate strength and yield rate from HVF is better than thermal recycling, and, consequently, the high recyclate value entirely overcomes the drawback of its relatively high recycling cost. The net profit of HVF is the second highest of all EoL options.

Finally, LE is less financially attractive than the recycling options, with the exception of mechanical recycling. The reason for this is that LE consumes high-cost virgin fibre in repairs which raises its costs, making the equivalent recyclate value lower than other options.

Moreover, in this study, the extra cost of waste treatment after LE which would be same with conventional waste treatment is excluded in the system boundary.

3.2 Sensitivity analysis

In the GF and CF recycling cost estimations above, all the variables have been estimated (section 1.2 in SI) or assumed as accurately as possible, but because of the maturity of the technologies and the limited cost transparency, some data may be inaccurate. This inaccuracy may have a large impact on the judgement of the 'optimal' EoL choice and on the judgement of industrial scale up feasibility. In this section, we will perform sensitivity analysis to evaluate the impacts of some key variables. The key variables include the recycling cost, the recyclate value of products from thermal recycling technologies, regional features in labour costs, equipment costs, energy costs and policy in landfill.

From the literature and industrial partners, the cost of each EoL option varies across a wide range which causes difficulties in estimations. To overcome this, we set a base case which adopts the most likely/most frequently appearing data and then perform the sensitivity analysis.

3.2.1 Recycling cost variations

3.2.1.1 Glass fibre

Here we evaluate the impact of recycling cost (using chemical recycling (Figure S4) and HVF (Figure S5) as examples) on net cost and identify the breakeven points. The assumptions are as follows. Firstly, transportation and pre-process costs are assumed to be the same as the initial setting since this data has been collected from industrial partners so should be representative of the actual cost and will not fluctuate strongly. Secondly, the cost of chemical recycling increases to twice that of the reference recycling cost (the fluidised-bed process). For this recycling cost coefficient of 200%, the net profit is $844.2/t. We find that the breakeven cost coefficient is 555%. When the cost coefficient increases over 555%, chemical recycling becomes unfavourable financially.

HVF has a similar high equipment requirement to chemical recycling, and the HVF needs ultra-high voltage pulses to break down the composite pieces which requires high processing energy and thus high energy cost. In the base case, the recycling cost of HVF is assumed to be 2.5 times that of the fluidised-bed process (i.e., the net cost of HVF GF is -$176.2/tonne). In the sensitivity analysis, the transportation and pre-process costs are set to be the same. As in Figure S5, the recycling cost coefficient varies from 100% to 300%. By increasing the recycling cost coefficient, the breakeven ratio is found to be 176%.

Following the above, since the recyclate has high value, chemical recycling is more tolerant to the recycling cost variation. Though the recycling cost is 5 times higher than for the fluidised-bed process, chemical recycling can still make a profit. The tolerance of HVF is much lower, with the breakeven point at 1.76 times the cost of the fluidised-bed process.

3.2.1.2 Carbon fibre

The overall cost of each EoL option, including the pre-process cost, transportation cost and recycling cost, is the variable to find the breakeven value.

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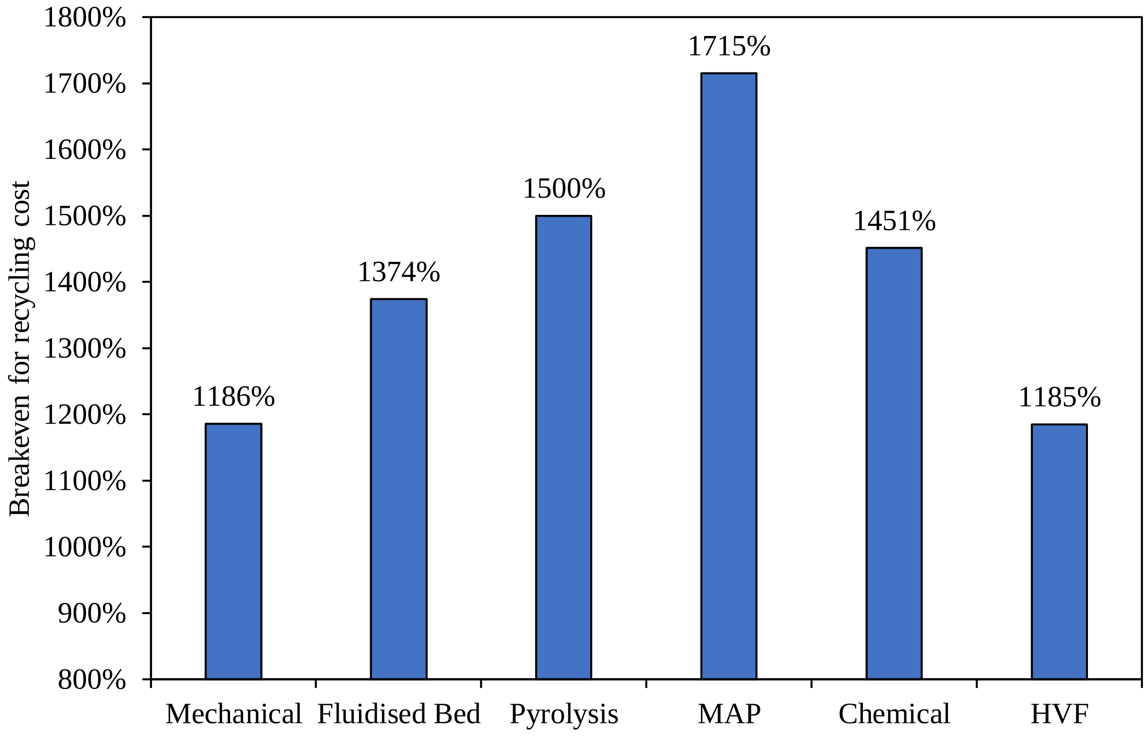

Figure 3: Recycling cost sensitivity test for CF EoL options.

As shown in Figure 3, the results reveal that breakeven for total recycling costs lies between 1185% and 1715%. This means that, given the high fibre value, the recycling cost is not a significant factor in the net profit/cost of the recycling operations. Even if the recycling cost is far higher than the base case estimation, making a profit from the recycling activity is still possible.

However, it is noted that the profit margin decreases with the increase of the recycling cost which reduces the incentive of stakeholders involved and could have negative impacts on the investment on CF recycling technologies. Moreover, the price of virgin CF is expected to fall over time due to increased production volume along with the increasing demand for CF (Pichler, 2016). In this case, if the virgin CF price keeps decreasing but the recycling cost remains the same, the recycling profit margin will also be reduced.

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3.2.2 Recyclate value variations

The recyclate value is another factor affecting the net profit/cost of EoL options. The recyclate value is affected by the unit recyclate value and the yield rate. We integrate them as a single variable to identify the breakeven recyclate value.

3.2.2.1 Glass fibre

As shown in Figure 4, mechanical recycling and chemical recycling can be profitable for the base case recycling cost. The recyclate value sensitivity analysis indicates that only when recyclate values are reduced by 69% and 41% respectively will their net profits fall to the breakeven value. The fluidised-bed process, pyrolysis, MAP and HVF in contrast show a loss in the base case; if, however, through technological developments, either their recyclate performance or yield rate can be increased such that their recyclate values improve by 130%, 71%, 35% and 26% respectively, they can achieve breakeven in recycling operations.

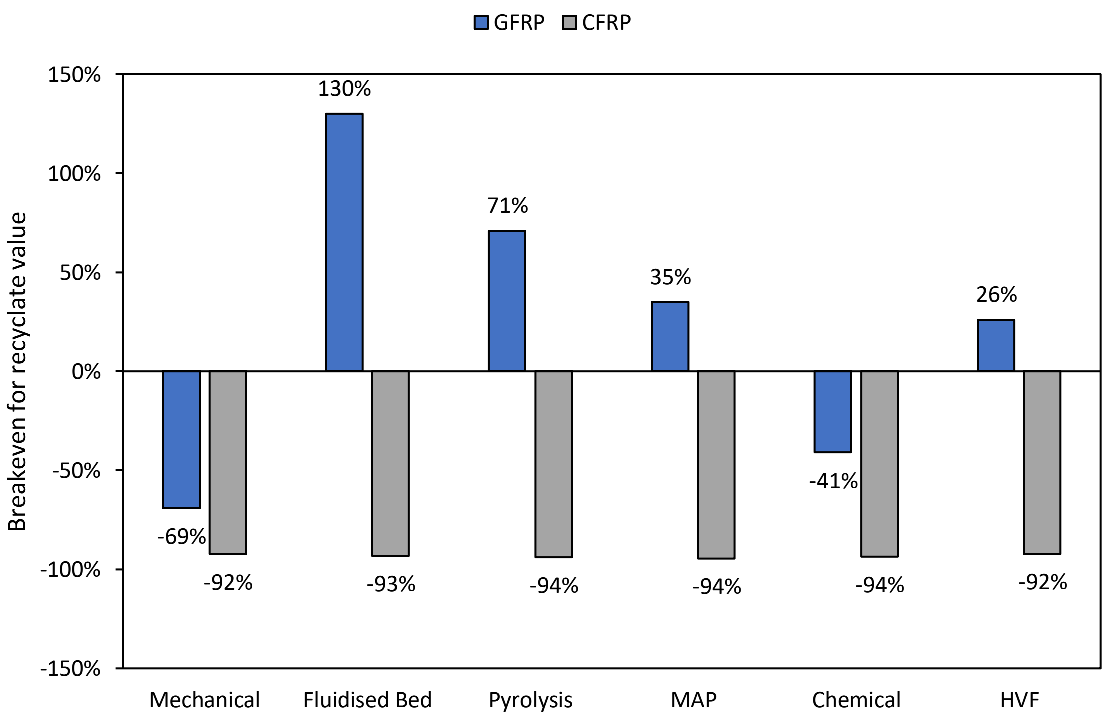

Figure 4 Breakeven points for GFRP and CFRP recyclate values.

3.2.2.2 Carbon fibre

In the base case, the breakeven of carbon fibre recyclate values for all EoL options are all less than -90% (Figure 4). In other words, even if recyclate values reduce by more than 90%, the recycling activities are still profitable indicating the recyclate value is not a key driving factor. Even if there is inaccuracy in the estimation of recyclate value, the net profit margin is relatively high.

3.2.3 Regional features

Four featured regions (i.e., China, Europe (the UK), the US and rest of the world) were selected which have similar wind energy installed capacities and wind industry development targets. We adopt the same regions for the following analysis.

The major direct costs of recycling processes consist of the labour cost, equipment cost and energy cost. These vary based on the regional geography, economy and technology. The effects of regional features on net cost are thus discussed.

Starting with the labour cost, in China the hourly wage for a well-trained worker is ¥35 ($5), which is much lower than that of western countries. Here, we assume the labour costs in Europe and the US are four times those of China (SalaryExpert, 2021).

Moreover, as China is a large manufacturing country with a very strong low/mid-end manufacturing industry, industrial equipment costs are relatively low. On the other hand, Europe has a strong high-end manufacturing industry and top-quality equipment, but at very high cost (Table S7). The US equipment is also advanced, but we are assuming generally the cost is fractionally lower than Europe. Hence, we assume that the equipment cost in Europe is five times that of China and the equipment cost in the US is four times that of China.

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Industrial electricity prices for major countries vary considerably (Figure S6). For instance, the electricity prices vary significantly between $42 to $315 per MWh in Europe. We choose the United Kingdom to represent Europe since the UK has one of the largest wind energy installed capacities in Europe, and also has a median electricity price for the region. The energy costs of the UK, the US and China are $148.6, $68.3, $126.8 per MWh, respectively. We have normalised the energy cost relative to the US and the labour cost and equipment costs relative to China in Table S8.

Pickering et al. (2000a) estimated the direct manufacturing cost of a fluidised-bed process plant and found energy costs represent 50%, labour costs 17% and other costs, mainly equipment cost, the remaining 33%. We assume the ratios of these costs for other EoL options are the same, then we apply the cost index in order to analyse the differences between regions. For example, the labour cost in China is assumed to be ¥280 ($40) per day. The labour cost in Europe and US is $160 per day, four times greater. Then we apply the same method to the energy cost and equipment costs. Results for the fluidised-bed process as an example are given in Table S9.

By applying the same method to the other EoL options, the costs for different regions can be obtained (Table S10). Generally, benefiting from the low labour and low equipment costs, the net profits of EoL options in China are higher than both the US and Europe. Looking at individual options, HVF has the most significant variations between regions. Since both the energy consumption and equipment costs are quite high, HVF benefits significantly from being in a region with low energy and low equipment costs. The net cost of HVF changes from having the second largest loss when in the EU (-$176.2/t) to making a profit when in China ($44.0/t). The other options also see noteworthy changes: MAP turns making a loss in Europe (-$61.7/t) to making a profit in China ($25.5/t), and the fluidised-bed process reduces its loss by 50%. Since financial performance is one of the most important factors in policy and the decision-making process, these changes will affect the choice of ‘optimal’ EoL option. At the stage of real policy making and commercial operation, local conditions as exemplified above should be carefully considered.

3.2.4 Regional landfill cost variations

The landfill costs of the UK (used as reference in the base case), the US and China have been compared with three ready-to-go/lab-scale recycling technologies, using costs for Europe (Figure S7). In the base case, the net costs of the EoL options have been compared with UK landfill costs since most cost data are collected from the UK and Europe. Europe has some of the most restrictive environmental regulations in the world, including high landfill costs – and in particular the UK landfill tax has significantly increased over the last twenty years (£7/t or $10.9 in 1996 to £94.15/t or $116.45 in 2020 (WRAP (Waste & Resources Action Programme), 2019)). As shown in Figure S7, the cost of pyrolysis is less than the cost of UK landfill which leads to this option being favourable, based on financial incentives. However, since landfill costs in China and the US are only around $65 per tonne, 60% lower than that in the UK, the costs of these recycling options in China and the US are much higher than the corresponding landfill costs, which would instead lead to these operations being financially unfavourable. The development of such recycling technologies would then be driven by government support rather than the market. However, if the landfill tax/cost continues to increase to encourage environmental protection, such as to over $200/t in the future, this would push the development of recycling and make the current high-cost technologies more favourable. Strong policy, such as banning composite landfill, or financial subsidy, would otherwise be needed.

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4 Summary and conclusions

In this paper, we have used a quantitative method, first building a financial performance model for wind turbine blade EoL options, then evaluating and comparing the financial performance for all available EoL options, and finally performing a sensitivity analysis to verify the result. Regarding the recycling of GF, the challenge is the low prices of the virgin GF ($1.6/kg) acting as a barrier for the reuse of the recycled material. The situation for CF waste is different due to the high value of CF, reducing the impact of recycling cost and shifting the dominant factors to recyclate value.

Of the ready-to-go recycling options for GF waste, mechanical recycling is the only one to make a profit. The high energy consumption of the current pyrolysis process gives losses in a similar range to landfill cost, over $140 per tonne, for recycling GF blade waste. R&D investments are required to increase process efficiency and reduce energy consumption to further reduce the recycling cost. On the other hand, for CF waste the net profit for mechanical recycling is the lowest, 50% less than the other ready-to-go technologies. The net cost of pyrolysis is quite favourable and indicates that this is attractive as a ready-to-go recycling process. Of the lab-scale technologies (fluidised-bed process, MAP, chemical recycling and HVF), chemical recycling has been found to be the most profitable.

In addition to the technological limitation, regional features and local policies may determine the choice of an ‘optimal’ wind turbine blade EoL option. The costs of all these recycling options in China and the US are much higher than the corresponding landfill costs, which would lead to these operations being financially unfavourable. The development and introduction of such recycling technologies would then be driven by government support rather than the market. However, if the landfill tax/cost continues to increase to encourage environmental protection, to over $200/t in the future, this would push the development of recycling and make the current higher cost technologies more favourable. Strong policy, such as banning composite landfill, or financial subsidy, would otherwise be needed.

EoL composite waste treatment is a cross-sector challenge and not solely a challenge for the wind industry. All the composite-using sectors must work together to find cost-effective solutions and value chains for the combined volume of composite waste. Apart from the recycling technologies, suitable markets for the recycled material should be identified by adopting a cross-sectoral approach. Recycled material from wind turbine blades may not meet the designed mechanical performance for closed-loop reuse in the wind power industry, but it could be used in other sectors such as automotive and construction. The findings from this paper are thus significant to inform better decision-making among all available recycling methods based on the commercial value of recycling options for both GF and CF composite waste from wind power industry.

Declaration of competing interest

The authors declare no competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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