End-of-life possibilities of Wind turbine blade: 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 2024. 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, thereby polluting the environment. Wind turbine blades are mainly made from lightweight thermoset composites (glass fiber/ carbon fiber), which are economically challenging to recycle. This study aims to understand the economic feasibilities of recycling technology options for blade waste management. An appropriate quantitative method is employed, 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 fluidized-bed recycling is the optimal options among the available technologies, and chemical recycling is the optimal option for technologies currently available only at lab scale.

Keywords:

Composite wind turbine blade, end of life, recycle, wind energy

Introduction

Wind energy is a promising source 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. Considering the operational stage of life cycle alone of wind turbine, it was categorized as clean energy technology. Electrical energy from Mechanical energy is produced due to Kinetic energy available from the rotation of wind turbine blade. A typical wind turbine blade is shown in figure 1.

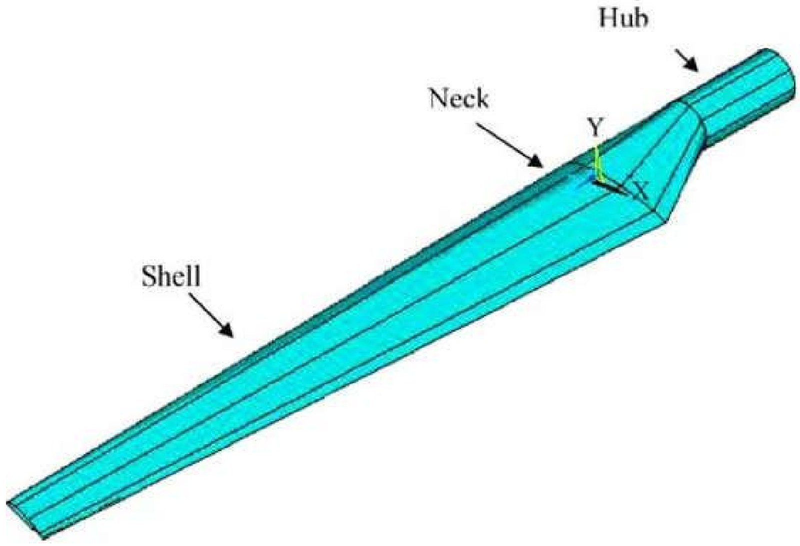

Figure 1: Wind Turbine Blade

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). The major constituents of Wind turbine blades material are composite materials comprising thermosetting resin and glass fiber (GF) or carbon fiber (CF). They are lightweight with a cross-linked matrix material structure resulting in high fatigue resistance and mechanical strength. This structural behavior of this material makes them difficult to recycle (Pickering, 2006). Cooperman et al., 2021; Lichtenegger et al., 2020; Liu and Barlow, 2017; Sommer et al., 2020 reported that 789,000 tonnes of composite waste were generated in 2020 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), and it is 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 Rs.12,000 per tonne including a landfill tax of Rs.9,500 per tonne WRAP (Waste & Resources Action Programme) 2019. In India also there is such proposal to imply tax for landfill of solid wastes. A photographi view of damaged EoL of Wind turbine blade is shown in Figure 2.

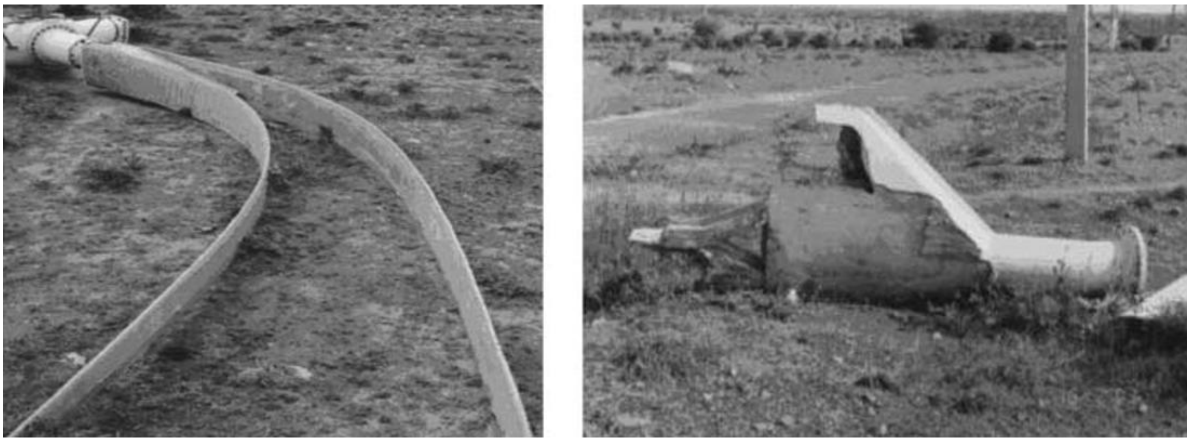

Figure 2: Failed Composite Wind Turbine Blades

Composite waste can be recycled via mechanical recycling, thermal recycling viz. pyrolysis and fluidized bed processes or chemical recycling (Krauklis et al., 2021; Meng et al., 2018a; Rani et al., 2021; Zhang et al., 2020). Mechanical recycling in this context normally involves grinding the composite to produce particles typically between 50 µm and 10 mm 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 Fiber Ltd. in the UK with a recycling capacity of 2000 t/yr (ELG Carbon Fiber Ltd, 2021)). In this process, the resin is thermally decomposed into hydrocarbon products, allowing recovery of the carbon fibers. Similarly, the fluidized bed recycling process oxidizes the polymer matrix to enable carbon fiber 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 fibers at lower temperature than thermal processes, though often at higher pressure (Mattsson et al., 2020; Keith et al., 2016a). The environmental and financial benefits of recycling are dependant on the waste type and the EoL processes used. If some of the recovered fibers 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 (Karuppannan et al, 2020a; Meng et al., 2018b).

A comparative study of costs for existing recycling technologies for both GF and CF composites waste is missing. In this paper, an attempt is made to compare the economic performance of different recycling technologies for blade waste management. The methodology of cost analysis including the calculation logic and parameter settings of the process-based cost model (Bloch and Ranganthan, 1991) are being discussed. In the EoL processes, each blade is disassembled, and the waste is classified. Blade materials fall into three categories: 100% glass fiber (GF), 100% carbon fiber (CF) and a mixture of the two (hybrid). The analysis is simplified by analyzing the GF and CF fractions of the hybrid separately and combining in the appropriate proportions for the blade type. Hence, the financial performance of the EoL options by considering material type (GF and CF) but not specific blade models are analyzed. A cost analysis is performed for GF and CF respectively considering the recycling cost and recyclate value of each fiber EoL option. Differing from previous studies, this paper provides a transparent and comparative economic assessment of different GF and CF 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 amongst all available recycling methods based on the commercial value of recycling options for both GF and CF when facing carbon tax and stricter regulations.

Methods:

The recycling process of wind turbine blade consists of four steps:

(i) Dismantling the wind turbine
(ii) Disassembling and cutting the wind turbine blades into meter-sized or smaller scrap convenient for transportation
(iii) Transporting the scrap to the recycling centre
(iv) Recycling the scrap

This study focusing on recycling the wind turbine blade material and producing the recyclate as stated in 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 viz. fiber, filler, resin and energy. The net cost (C_n) can be calculated using the following expression.

$$C_n = (C_d + C_t + C_r) - (I_f + I_{fr} + I_r + I_e)$$

= Cost of disassembling; = Cost of transportation; = Cost associated with recycling; = revenue from fiber recyclate; = revenue from filer recyclate; = revenue from resin recyclate; = revenue from energy recovery.

For each EoL option, the recycling process is briefly described and then the recycling cost and recyclate value are elaborated. 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, China and India markets is converted into the Indian Rupees (Rs.). Wind turbine blade EoL waste processing routes are presented in Figure 3. 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.

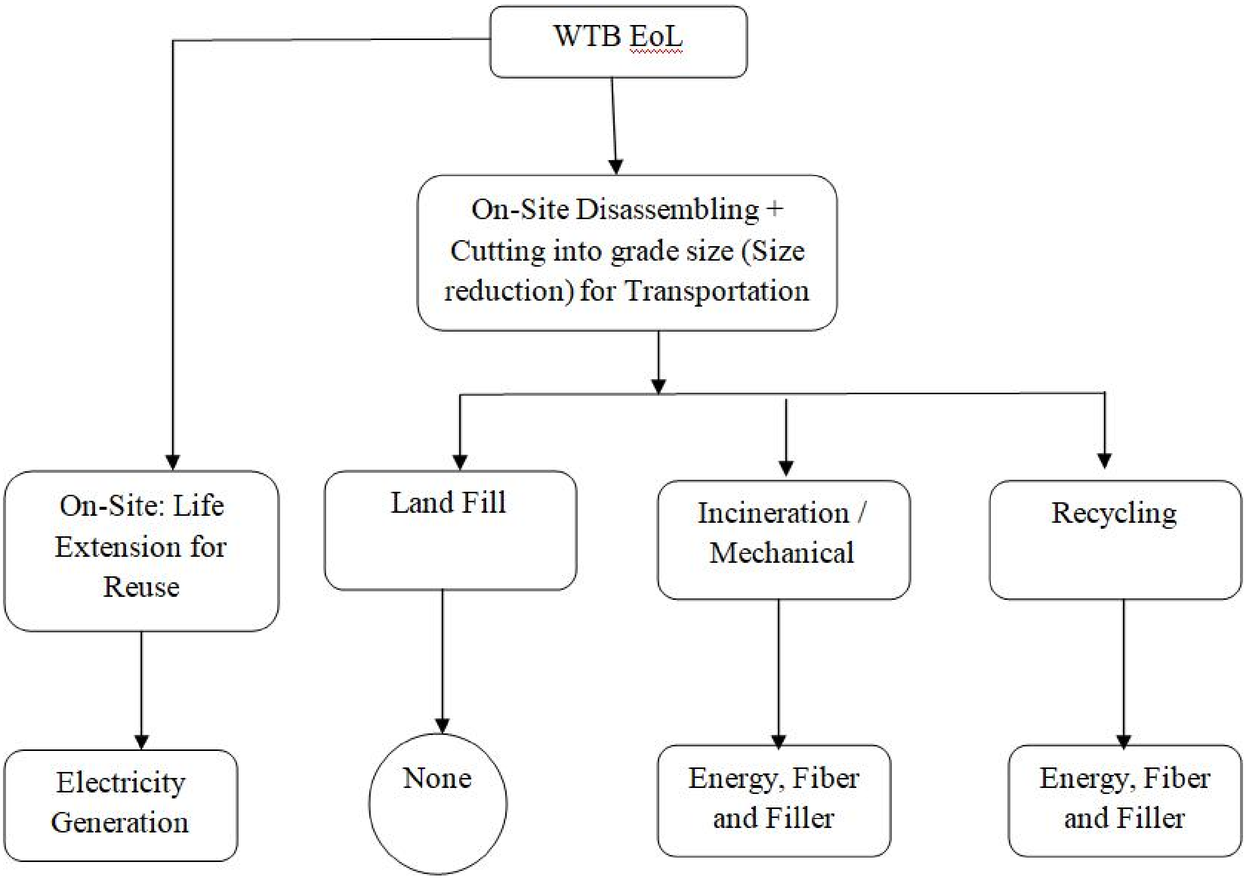

Figure 3: Various modes of flow of Wind Turbine Blade End of Life route

2.1. Value of Wind Turbine Blade Material:

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), it is assumed 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 1 and Table 2.

The key assumptions regarding recyclate value are as follows:

- The value of the recycled fiber is assumed to be proportional to its tensile strength. If the strength of the recycled fiber is 80% of virgin fiber, then its value is 80% of virgin fiber.
- 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. Hence, all the recycled fiber is short fiber, and thus the recycled fiber value is calculated based on virgin short fiber.
- 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. Cost incurred for Cutting and disassembly:

The cutting and disassembly cost for composite waste is ranging from Rs.1000 to Rs.6000 per tonne, varying between regions (Liu and Barlow, 2015). An average value of Rs.3500/- per tonne is used in the base case.

2.3. Cost incurred for Transportation:

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. This study focuses only on onshore blades. 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).

2.4. Alternates for Waste EoL:

Nine approaches are considered to handle the wind turbine blade waste for both glass fiber and carbon fiber wastes, of which two do not involve recycling i.e. Land filling and Life extension (LE) 5 years. Incineration, Mechanical recycling and Pyrolysis use well proved established technologies. The other recycling technologies considered (Fluidized 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 summarized in Tables 1 and 2.

For the recycling process

- Wind turbine blades are made of two major materials: fiber and resin. Other parts of the structure include copper lightning protectors, steel root secure bolts and the sandwich core material, which is made from balsa or polymer foam. Those weight fractions of thee supporting components are less than 5% 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% fiber 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 +((fiber yield rate * fiber performance * virgin fiber cost +filler yield rate * filler cost) * fiber 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.

Table 1: Recyclate Value of Glass Fiber

Glass fiber	Fiber yield rate (%)	Virgin fiber value (in lakhs of Rs.) per tonne	% virgin performance conserved in recyclate	Filler yield rate (%)	Virgin filler value (in lakhs of Rs.) per tonne	% virgin performance conserved in recyclate	Feedstock fiber content (%)	Resin yield rate (%)	Virgin resin value (in lakhs of Rs.) per tonne	% virgin performance conserved in recyclate	Feedstock resin content (%)	Overall process yield (%)	Years extended	Recyclate value (in lakhs of Rs.) per tonne
Landfill	Nothing	--	--	--	--	--	--	--	--	--	--	--	--	--
Incineration	Energy recovery alone	--	--	--	--	--	--	--	--	--	--	--	--	0.05
Mechanical	58.3[3]	1.11	78.0[3]	41.7	0.264	100	60	0	0	0	40	95	--	0.349
Fluidized-Bed	44.0[1]	1.11	50.0[1]	7.6	0.264	100	60	0	0	0	40	95	--	0.149
Pyrolysis	56.0[2]	1.11	52.0[2]	14.0	0.264	100	60	0	0	0	40	95	--	0.205
MAP	56.0[6]	1.11	52.0[6]	14.0	0.264	100	60	0	0	0	40	95	--	0.205
Chemical	100.0[5]	1.11	58.0[5]	0.0	0.264	100	60	100	4.735	50	40	95	--	1.265
HVF	90.0[4]	1.11	88.0[4]	0.0	0.264	100	60	0	0	0	40	95	--	0.499
Life extension 5 years		1.396	--	--	0.264	--	60	--	4.735	--	40	--	5	0.683

References: 1 (Pickering et al., 2000a), 2 (Cunliffe et al., 2003), 3 (Palmer et al., 2009), 4 (Rouholamin et al., 2014), 5 (Keith et al., 2016a), 6 present study

Table 2: Recyclate Value of Carbon Fiber

Glass fiber	Fiber yield rate (%)	Virgin fiber value (in lakhs of Rs.) per tonne	% virgin performance conserved in recyclate	Filler yield rate (%)	Virgin filler value (in lakhs of Rs.) per tonne	% virgin performance conserved in recyclate	Feedstock fiber content (%)	Resin yield rate (%)	Virgin resin value (in lakhs of Rs.) per tonne	% virgin performance conserved in recyclate	Feedstock resin content (%)	Overall process yield (%)	Years extended	Recyclate value (in lakhs of Rs.) per tonne
Landfill	Nothing	--	--	--	--	--	--	--	--	--	--	--	--	--
Incineration	Energy recovery alone	--	--	--	--	--	--	--	--	--	--	--	--	0.05
Mechanical	0.0	20.091	0.0[5]	100.0	4.72	100	60	0	0	0	40	95	--	2.691
Fluidized-Bed	60.0	20.091	75.0[4]	7.6	4.72	100	60	0	0	0	40	95	--	5.358
Pyrolysis	56.0	20.091	80.0[3]	14.0	4.72	100	60	0	0	0	40	95	--	5.507
MAP	56.0	20.091	80.0[5]	14.0	4.72	100	60	0	0	0	40	95	--	5.507
Chemical	100.0	20.091	96.0[1]	0.0	4.72	100	60	100	4.735	50	40	95	--	11.893
HVF	90	20.091	83.0[2]	0.0	4.72	100	60	0	0	0	40	95	--	8.554
Life extension 5 years	--	25.373	--	--	4.72	--	60	--	4.735	--	40	--	5	4.279

References: 1 (Bai et al., 2010), 2 (Weh, 2012), 3 (Onwudili et al., 2013), 4 (Meng et al., 2017), 5 present study

3. Results and discussion

Financial viability of different EoL options for GF and CF wind turbine blade waste are analyzed in this section. Sensitivity analysis is used to predict how comparative costs may change for the future, so indicating which processes may become favorable as recycling technologies and infrastructure evolve.

3.1. Comparative costs for EoL processes

Glass fiber waste:

The total recycling costs, recyclate values and net profits of each glass fiber EoL option are summarized in Figure 4. This overview illustrates our key findings: three EoL options make a profit (i. e., mechanical and chemical recycling, and Life Extension (LE) for 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 Rs.5,000 per tonne waste, this makes the net cost of incineration lower than landfill.

Among the 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 Rs.12,000 per tonne.

Among the technologies like fluidized 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 Rs.5,200 per tonne. 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 fiber recovered from HVF, however, is considerably stronger than the fiber 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.

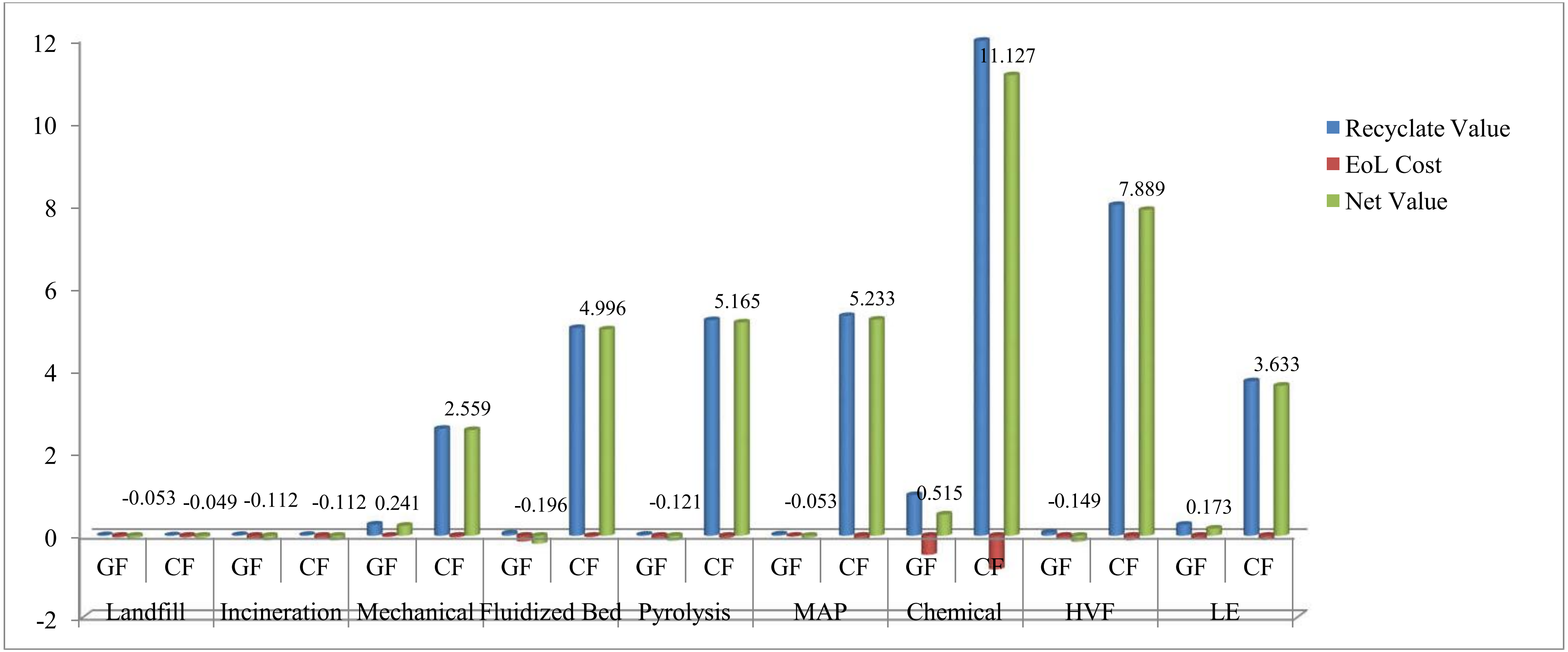

Figure 4: Comparison of Cost, recyclate value and net profit for EoL options for GF and CF waste from wind turbine blades (amount in lakhs of Rs.).

The LE plan is profitable with a margin of Rs.17,000 per tonne, 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) have started offering a life extension programme to their customers (Siemens Gamesa, 2021) using service standards launched in March 2016 (DNV, 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.

Carbon fiber 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 6, 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 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 fibers 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 fibers from the fluidized 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 fiber and its capability of recovering resin content. HVF's position regarding CF is completely different to its position for GF waste (-Rs.15,000 per tonne, 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 fiber 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 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 judgment of the ‘optimal’ EoL choice and on the judgment 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 labor 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.

3.3. Recycling cost variations

Glass fiber:

The impact of recycling cost using chemical recycling and HVF on net cost were evaluated and the breakeven points were identified. The assumptions considered are as follows.

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.

The cost of chemical recycling increases to twice that of the reference recycling cost (the fluidized-bed process). For this recycling cost coefficient of 200%, the net profit is Rs.72,000 per tonne. Using the above, breakeven cost coefficient is determined as 555%. When the cost coefficient increases over 555%, chemical recycling becomes unfavorable 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 require high processing energy and thus high energy cost. In the base case, the recycling cost of HVF is taken as 2.5 times that of the fluidized-bed process (i.e., the net cost of HVF GF is – Rs.15,000 per tonne). In the sensitivity analysis, the transportation and pre- process costs are set to be the same. 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 fluidized-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 fluidized- bed process.

Carbon fiber:

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. As shown in Figure 5, the results reveal that breakeven for total recycling costs lies between 1185% and 1715%. This means that, given the high fiber 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.

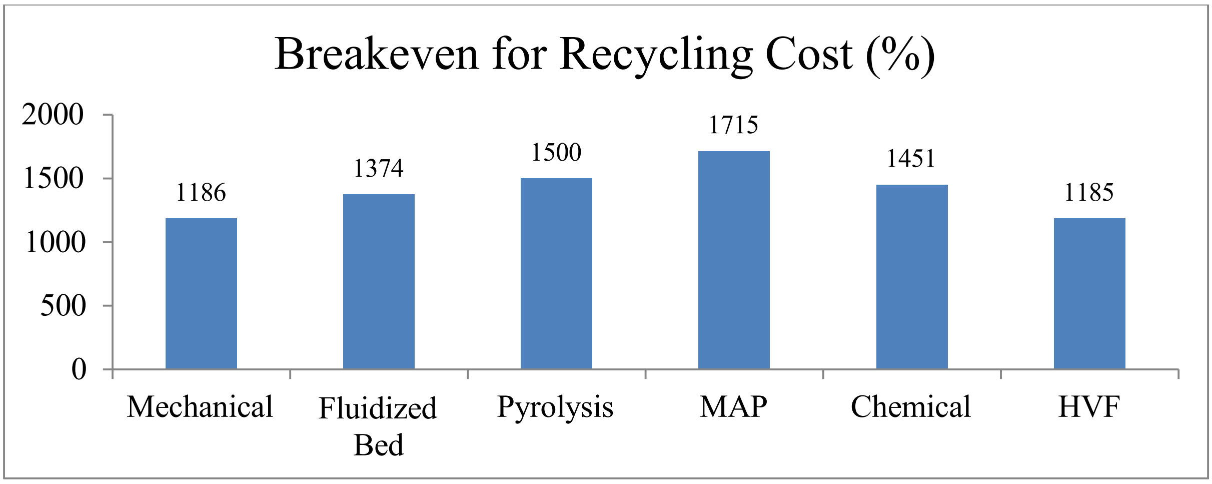

Figure 5: Recycling cost sensitivity variation for CF EoL options.

3.4. 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.

Glass fiber:

Mechanical recycling and chemical recycling can be profitable for the base case recycling cost, as evident from figure 6. 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 fluidized-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.

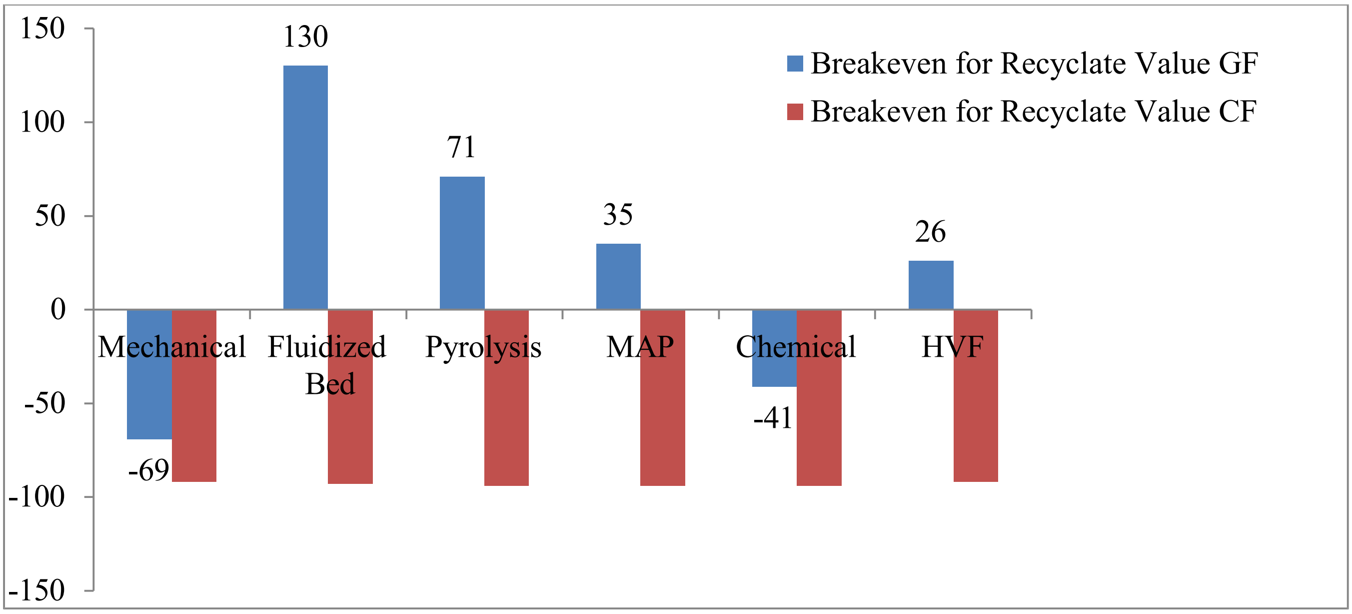

Figure 6: Breakeven points for GF and CF recyclate values

Carbon fiber:

In the base case, the breakeven of carbon fibre recyclate values for all EoL options are all less than − 90%. 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.

3.5. Regional features.

Four featured regions (i.e., India, China, Europe, and US) were selected which have similar wind energy installed capacities and wind industry development targets. The major direct costs of recycling processes consist of the labor 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 labor cost, in India the hourly wage for a well- trained worker is Rs.250, which is much lower than that of other regions. Here, we assume the labor costs in China is two times than that of India and for Europe and the US are four times those of India (Salary Expert, 2021). Moreover, as India 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. 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 India and the equipment cost in the US is four times that of India and that in China is two times than that of India. Industrial electricity prices for major countries vary considerably. For instance, the electricity prices vary significantly between Rs.3,500 to Rs.27,000 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, China and India are Rs.12,650, Rs.5,900, Rs.10,800 and Rs.7300 per MWh, respectively.

Pickering et al. (2000b) estimated the direct manufacturing cost of a fluidized-bed process plant and found energy costs represent 50%, labor 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 analyze the differences between regions. For example, the labor cost in India is Rs.2,000 per day. The labor cost in China is Rs.3800 per day, two times greater and that in Europe and US is Rs.10,000 per day, five times greater. Then we apply the same method to the energy cost and equipment costs. By applying the same method to the other EoL options, the costs for different regions can be obtained. Generally, benefiting from the low labor and low equipment costs, the net profits of EoL options in India are higher than China, 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 (Rs. – 15,000 per tonne) to making a profit when in India (Rs.3700 per tonne). The other options also see noteworthy changes: MAP turns making a loss in Europe (Rs. – 5,300 per tonne) to making a profit in India (Rs.2,200 per tonne), and the fluidized-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.

3.6. Regional landfill cost variations:

The landfill costs of the UK, US, China and India have been compared with three ready-to-go/lab-scale recycling technologies. 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 (Rs.1000 per tonne in 1996 to Rs.10,000 per tonne in 2020 (WRAP (Waste & Resources Action Programme), 2019)). The cost of pyrolysis is less than the cost of UK landfill which leads to this option being favorable, based on financial incentives. However, since landfill costs in China and the US are only around Rs.5,500 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 unfavorable. 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 Rs.17,000 per tonne in the future, this would push the development of recycling and make the current high-cost technologies more favorable. Strong policy, such as banning composite landfill, or financial subsidy, would otherwise be needed.

4. Conclusions:

In this paper, quantitative method is employed, 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 (Rs.135/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. Among the 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 Rs.12,000 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 favorable and indicates that this is attractive as a ready-to-go recycling process. Of the lab-scale technologies (fluidized-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 unfavorable. 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 Rs.17,000 per tonne in the future, this would push the development of recycling and make the current higher cost technologies more favorable. 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. 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 amongst all available recycling methods based on the commercial value of recycling options for both GF and CF composite waste from wind power industry.

List of Abbreviations:

CF	:	Carbon fiber
EoL	:	End of Life
GF	:	Glass fiber
GHG	:	Green House Gases
HVF	:	High voltage fragmentation
LE	:	Life Extension

MAP : Microwave assisted Pyrolysis
WTB : Wind Turbine Blade

Declarations:

Availability of data and materials:
Original work carried out by the authors using the existing wind farm located at Aralvaimozhi, Tamilnadu, India.

Competing interests:
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors' contributions:
Conceptualisation: JSR; Methodology: JSR; Software: SJJ; Formal Analysis: JSR, SJJ; Investigation: JSR, SJJ; Writing – Original Draft: SJJ; Writing – Review & Editing: JSR, SJJ; Visualisation: JSR, SJJ.

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