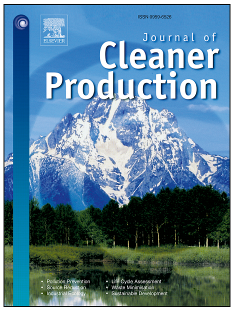

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PII: S0959-6526(18)33745-4
DOI: https://doi.org/10.1016/j.jclepro.2018.12.043
Reference: JCLP 15101

To appear in: *Journal of Cleaner Production*

Received Date: 27 July 2018
Revised Date: 29 November 2018
Accepted Date: 5 December 2018

Please cite this article as: Liu P, Meng F, Barlow CY, Wind turbine blade end-of-life options: An eco-audit comparison, *Journal of Cleaner Production* (2019), doi: https://doi.org/10.1016/j.jclepro.2018.12.043.

Wind Turbine Blade End-of-life Options: An Eco-audit Comparison

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Abstract

Wind energy has developed rapidly over the last two decades to become one of the most promising economical and green sources of renewable energy, responding to concerns about use of fossil fuels and increasing demand for energy. However, attention is now turning to what happens to end-of-life wind turbine waste, and there is scrutiny of its environmental impact. In this study, we focus on one aspect of this, the blades. We analyse and compare end-of-life options for wind turbine blade materials (mainly glass fibre reinforced plastic and carbon fibre reinforced plastic) in terms of environmental impact (focusing on energy consumption), using our own data together with results gathered from the literature. The environmental impacts of each end-of-life option are discussed, looking at processing energy consumption, the recycling benefits and the effect of blade technology development trends. There is considerable variability in the results, and lack of consensus on predictions for the future. We therefore analyse the results using a range of different scenarios to show how the 'optimal' solutions are influenced by trends in blade composition and end-of-life process development. The most environmentally favourable process is dependent on whether the materials used for the blades are glass fibre composite or carbon fibre composite. The extent to which process improvement might affect the viability of different end-of-life processes has been assessed by looking at 'crossover' points for when the environmental impact becomes favourable. This analysis gives new insight into areas where research into process technologies could be targeted to enable significant end-of-life environmental benefits.

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

1 Introduction

Wind energy has developed rapidly over the last two decades to become one of the most promising economical and green sources of renewable energy, responding to concerns about use of fossil fuels and increasing demand for energy (Hannah and Max, 2017). The first generation of commercial turbines are reaching the end of their design life, and attention is just starting to turn to the problem of what will happen to the waste as the generators are decommissioned (Liu and Barlow, 2017). The environmental implications are significant, but at present there are limited estimates of the potential magnitude of the problem. We are addressing one aspect of this, focusing on the blades. A large part of these high-value components is fibre composite (glass fibre reinforced plastic (GFRP) and carbon fibre reinforced plastic (CFRP)), for which there is currently no satisfactory recycling route. The composites recycling industry is developing, and one of its requirements in the coming years will be estimates of the environmental benefits that composites recycling may bring (Meng et al., 2018). In this study, we analyse the end-of-life (EoL) options for wind turbine (WT) blades in terms of environmental impact and then compare them to determine an 'optimal' solution which minimises environmental impact.

Several studies have reviewed the available EoL options for general composite waste (Jagadish et al., 2018; Li et al., 2016; Naqvi et al., 2018). In a comparatively early study, Halliwell (2006) raised awareness of the environmental problem arising from composite used in vehicles. She pointed out that volumes of composite in the automobile industry would rapidly increase as CFRP moved to large volume production cars from being used only in racing and high performance cars, and the concomitant waste problem would become increasingly serious. Halliwell reviewed the EoL options including landfill, incineration, mechanical recycling, fluidised-bed recycling and pyrolysis recycling processes and suggested that successful composite recycling requires incentives, infrastructure, recycling techniques and market commitment. The major barrier for composite recycling at that time was identified as the low market demand for recyclate. Pickering (2006) reviewed the EoL options from a technical perspective and stated that, due to the major barrier in composite recycling being the significant performance loss of recyclate, the low value of recyclate resulted in a weak economic incentive to recycle. He held that new legislation or supportive policies would be necessary to provide a driver for composite recycling. A more recent review by McConnell (2010) includes the progress in composite recycling technologies, specifically the new microwave assisted pyrolysis (MAP) and chemical recycling techniques. He stated that the new and updated technologies have enabled the launch of the carbon fibre (CF) recycling industry for aviation manufacturing waste. More up-to-date research has reported on the few commercial pyrolysis CF recycling plants and highlights the benefits of recycling including the low energy consumption of recycling compared to the high cost of producing new CF (Job, 2014; Job et al., 2016). However, for the goal of the present research, these studies have two major limitations. Firstly, they cover only a few EoL options but do not provide comprehensive coverage of all options. Secondly, they mainly focus on the composite waste from the automobile and aviation industries; WT blade waste has not been well addressed. With the rapid development of wind energy (Liu and Barlow, 2017), composite usage in wind turbines now forms a major part of the composites market, ranking second by usage just after the aviation and defence sector (Holmes, 2014). The EoL waste from wind turbine blades is predicted to exceed 500 kilo tonnes annually by 2029 and to continue increasing rapidly thereafter (Liu and Barlow, 2017), providing strong motivation for a focus on this type of composite waste.

WT blade waste has the following specific features:

- It has a complex and mixed material composition including fibre, resin, core material and supportive material.
- There is variation between WT blades in terms of their structural design, size and material composition.
- The large size of the blade may cause difficulties in dismantling, transportation and size reduction.

In addition:

- Glass Fibre (GF) /GFRP (the major material) is of low value.
- The thermoset resin is cross linked and cannot be remoulded.

These features make WT blades more challenging to process than general composite waste. Investigations have attempted to address this problem, either from the start, looking at raw materials, or from the end, examining end-of-life processes. For the raw materials, natural fibres such as flax and bamboo have been proposed as substitutes for GF as they have lower environmental impact. However due to their limited strength and problems of uniformity, this concept is still under development (Brøndsted et al., 2005; Corona, 2015, 2013; Halliwell, 2010; Liu, 2014). Another approach has investigated using thermoplastic resins for the composite matrix, enabling remanufacture (Marsh, 2010). However, due to their high viscosity and high costs thermoplastic matrices have not yet been used in commercial WT blade production. Turning to the end of the lifecycle, the possible end-of-life (EoL) processes for WT blade waste have been summarised and discussed in a few studies (Andersen et al., 2014; Beauson et al., 2013; Beauson and Brøndsted, 2016; Larsen, 2009); these, however, provide incomplete coverage of the advantages and disadvantages of EoL options, and mostly in a qualitative way. The research so far thus either covers one part of the WT blade EoL issue, or qualitatively assesses the problem without enough supporting data, or in minimum detail. There is a clear knowledge gap here.

The present study has found from visits to WT blade manufacturers and from information gathered from industry exhibitions that there is good general awareness in the sector that EoL is a problem, but there is little appreciation of the magnitude of its severity and lack of guidance on appropriate options. We are therefore using a quantitative approach to provide a thorough analysis of the EoL options in terms of environmental impact, aiming to formulate guidelines to aid industry and policy makers.

In the first part of this paper, relevant literature is reviewed and the incentives for undertaking the analysis of EoL options are explained. The environmental impacts of each EoL option are then discussed, looking at EoL processing energy consumption, the recycling benefits and the effect of blade technology development trends. In the final section, we integrate our findings with data from the literature on environmental impact, proposing different scenarios of future predictions to provide recommendations for 'optimal' solutions. We have used a sensitivity analysis approach to enable us to work with uncertain data. The extent to which process improvement might affect the viability of different end-of-life processes has been assessed by looking at 'crossover' points for when the environmental impact becomes favourable. This analysis also enables new insight into where the greatest benefits would derive from developments in EoL processes.

2 Methodology

An eco-audit is a streamlined lifecycle assessment that enables comparison of environmental impact of different products, materials and processes, focusing only on energy consumption and CO_2 emissions as the most significant indicator of impact (Ashby, 2009). This metric is calculated for each phase of life of a product: material, manufacture, transport, use and disposal. The dominant phase is identified as that with the largest energy consumption and the greatest CO_2 burden. The initial focus is then on the dominant phase since it has the biggest potential for reduction. An eco-audit provides a well-documented and established basis for making comparisons of environmental impact arising from different processes and lifecycle paths (Ashby, 2009). We have chosen to use energy consumption as the sole measure of environmental impact, in line with eco-audit methodology (Ashby et al., 2009).

2.1 Calculation logic and hypothesis

Here we provide definitions before outlining in the next section the steps taken and the underlying hypothesis. The *lifetime impacts* are the sum of the blade lifetime environmental impacts from the manufacture, transportation and operation and maintenance (O&M) stages. The *total lifetime impact* also includes the *EoL impact*. The *recycling benefit* of an EoL option is defined as the equivalent environmental impact of manufacturing the recyclate or the energy recovered through EoL processes: a negative environmental impact is desirable as it means energy is regained by the process. The *net impact* is calculated by adding the *recycling benefit* of the EoL option to the *lifetime impact*. Details will be given in Sections 2.3 and 2.4.

$$\text{Net impact} = \text{Lifetime impact} + \text{EoL impact} + \text{Recycling benefit}$$

In order to assess the effect of blade material composition we first select three similar-sized blade models, made with full GF, a hybrid of GF and CF, and full CF respectively. Blade lifetime environmental impact data have then been calculated. As there is no full CF blade data provided in previous studies, this is calculated as detailed in Section 2.2. EoL processing energies collected from the literature are then multiplied by the blade's mass to give the energy demand for recycling a blade. Recyclate yield rates are included to derive the recycling benefits. The *lifetime impact* plus the *recycling benefits* constitutes the *net impact* of each EoL option. Finally, the *net impact* of each EoL option is compared using impact from landfill as the benchmark, and the 'optimal' EoL option in terms of environmental performance is then discussed. The logic flow is presented in Figure 1 as shown below.

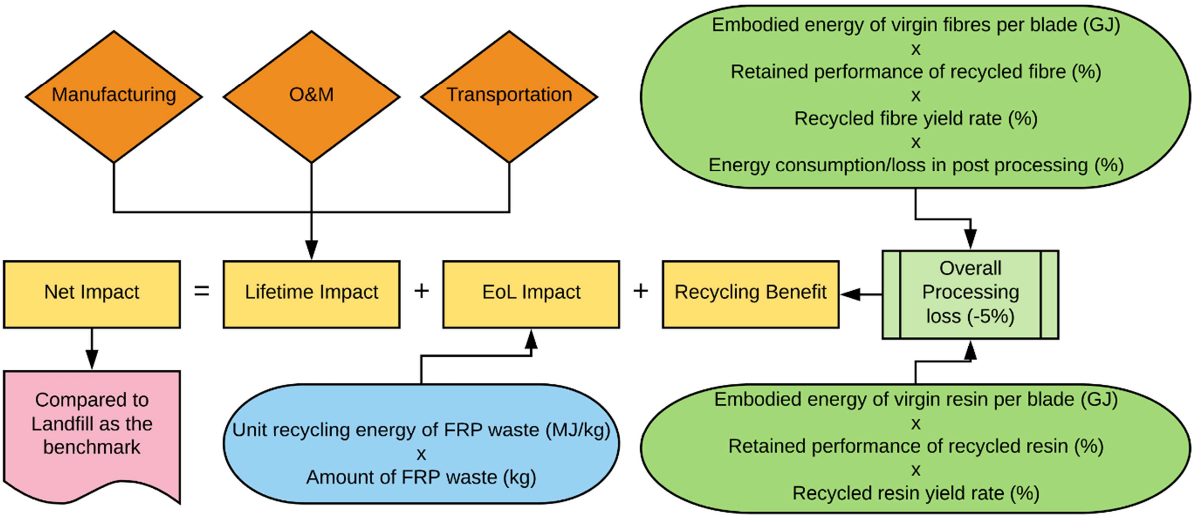

Figure 1: Schematic logic flow for net impact calculation. O&M= operation and maintenance; FRP= fibre reinforced plastics including glass fibre reinforced plastics and carbon fibre reinforced plastics; EoL= end of life.

The major hypothesis in this model is that the recyclate benefit is assumed to be proportional to its tensile strength since tensile strength is one of the most important properties of blade materials. For example, if the tensile strength of the recycled fibre is 80% that of virgin fibre, the environmental impact benefits of recycled fibre are taken to be 80% of the environmental impact of virgin fibre. Energy consumption (MJ/kg) is the main metric used to assess environmental impact.

2.2 Blade models

This research aims to use the most up-to-date blade models in its analysis. However, data for the recent 2 - 3 MW onshore turbines (EWEA, 2014; GWEC, 2016) are not available due to confidentiality. Instead, the analysis uses the second-most-recent 1.5 - 2 MW blade models, which are mainstream models installed between 2006 and 2013. Currently, most blades are made entirely of GF with a few being partially made of CF (hybrid). Limited by the high cost of CF, entire CF blades are quite rare. There was a few years ago a trend for more CF to be used in wind turbine blades, and while there has been much debate there is no indication that the use of CF in current WT blades has increased (Liu and Barlow, 2017; McKenna et al., 2016). In order to allow comprehensive coverage of EoL options, three similar-size blades of different types have been analysed as shown in Table 1. Commercial blades from the same manufacturer are used for GF and Hybrid, together with a hypothetical CF blade modelled on the hybrid blade. For the CF blade, the same material weight values of the hybrid blade are used for resin, supporting material and manufacturing consumables, and the density ratio used to estimate the weight, substituting CF for GF.

Model	GF blade (Manufacturer A)	Hybrid blade (Manufacturer A)	CF blade (Hypothetical)
Material	GF	CF spar cap GF for the rest	CF
Length/m	45.2	45.3	45.3
Rated Power/MW	1.5	2.0	2.0
Weight/tonne	7.58	7.50	6.24

Table 1: Blade model specification. GF blade is model 45.2A; Hybrid blade is DW93; both from Sinomatech.

2.3 Lifetime environmental impact

The blade lifetime environmental impact is calculated as outlined in Section 2.1. The manufacturing impact uses the weight of materials (kg) listed in the blade bill of materials (BoM) combined with the unit embodied energy of each type of material (kJ/kg). As shown in Table 2, the environment impact of GF, Hybrid and CF blades in the manufacture stage are 834.7 GJ, 1051.1 GJ and 1614.9 GJ, respectively. Because the unit impact of CF is 286 MJ/kg (Suzuki and Takahashi, 2005) which is much higher than the 52 MJ/kg of GF (Granta Design, 2016), the impact of the hybrid blade is 30% higher than that of the GF blade and the impact of the CF blade is double that of the GF blade.

	GF blade		Hybrid blade		CF blade	
In MJ	Energy	%	Energy	%	Energy	%
CF unidirectional	-	40.4%	268840	53.8%	1063904	71.9%
GF unidirectional	125528		-		-	
GF Bi/Triaxial fabric	160373		217069		-	
Resin	255090	54.8%	363515	40.3%	363515	24.5%
Curing Agent	76534					
Structural Adhesives	38914					
Structural Adhesives Curing Agent	17490					
Steel	3350	0.5%	5523	0.6%	5523	0.4%
Copper	1859	0.3%	10201	1.1%	10201	0.7%
Aluminium	500	0.1%	680	0.1%	680	0.0%
Balsa	2538	0.4%	633	0.1%	633	0.0%
PVC	12606	1.8%	12969	1.4%	12969	0.9%
Paint	7635	1.1%	5900	0.7%	5900	0.4%
Putty	5507	0.8%	16324	1.8%	16324	1.1%
Spray Adhesives	393	0.1%	1079	0.1%	1079	0.1%
Total Material Energy	708316	100%	902733	100%	1480728	100%
Total Consumable Energy	40308	-	68093	-	68093	-
Total Processing Energy	86065	-	80257	-	66033	-
Total Energy in MJ	834689	-	1051082	-	1614854	-
Total Energy in GJ	834.7	-	1051.1	-	1614.9	-
Total Energy Compared to GF blade		100%		126%		193%

Table 2: Manufacturing impact details of GF, Hybrid and CF blade models; GF blade is model 45.2A; Hybrid blade is DW93; CF blade is modelled based on DW93; all from Sinomatech.

The environmental impacts from the transportation and O&M stages are then estimated. Previous studies (Liu and Barlow, 2016) showed that the impact from transportation is between 1 GJ and 40 GJ per blade, dependent upon the mode of transportation and the distance. Since this is quite small compared to other energy consumptions and is not the key variable here, an average value of 20 GJ is adopted. The O&M impact has been estimated using two factors: materials and transportation of repair workers. The materials requirement has been set at an average level in which the amount of repair material required is 3% of the finished blade mass. The materials used in repair work consist of 60% fibre and 40% resin by weight. The O&M material impact is calculated using the material consumption multiplied by its unit environmental impact. For transportation, typically, a four person group is the most common size for routine blade maintenance and repair and one mid-size pickup truck is used (Zhang, 2016). We assume there are five major repair interventions for each blade during its lifetime and that the workers travel a 100 km round trip each time. Based on these, the energy consumption of an O&M car is then calculated as 1.6 GJ per blade (from 325 MJ/100 km for a typical diesel pickup truck, Nemry et al. 2008). Detailed lifetime impacts of the three blade models are listed in Table 3.

In GJ	GF blade	Hybrid blade	CF blade
Primary and Manufacture	834.7	1051.1	1614.9
O&M	20.7	26.2	43.6
Transportation	20.0	20.0	20.0
Total	875.4	1097.3	1678.5

Table 3: Detailed manufacture, Operation and maintenance and transportation environmental impacts for three blade models.

2.4 EoL environmental impacts

The EoL processes analysed here are landfill, incineration, mechanical recycling, fluidised-bed recycling, pyrolysis recycling, microwave assisted pyrolysis (MAP) recycling, chemical recycling (hydrolysis and solvolysis), high voltage fragmentation (HVF) recycling and blade life extension (LE). Most of the environmental impact data for these are obtained from the literature. Life extension environmental impacts have been calculated in the present study and are based on the material consumption and transportation demand.

Analyses in the literature of the processing energy required for the EoL options are very disparate, with a great variety of assumptions leading to a wide range of values. To enable comparisons we have used units of *MJ/kg waste* and defined a base case which adopts the most likely/most frequently appearing data. We then use a sensitivity analysis to evaluate the effect of variation of different parameters.

In the following, we will discuss the processing energy of EoL options, beginning with conventional waste processes and following with the ready to go/nearly ready to go and the lab-scale recycling technologies. A complete EoL process comprises four main stages: waste preparation (dismantling + size-reduction), transportation, recycling, and post processing. Most of the literature analyses do not include transportation energy as part of the recycling energy, so for comparative purposes we have excluded transportation for all technologies, including only energies for size-reduction and process energies for recycling. The assumption is that transportation energies for the different technologies will be comparable.

The conventional waste processes include landfill and incineration. Landfill CFRP waste requires 0.257 MJ/kg which can be broken down into 0.09 MJ/kg for shredding and 0.167 MJ/kg for landfilling operations (Li et al., 2016). In addition, we note that 0.143 MJ/kg is required for transportation, so a significant part of the total energy is excluded from our analysis. We assume in this study that the energy consumption for landfill disposal is 0.257 MJ/kg for both CFRP and GFRP.

Turning to incineration, we note that heat or power can be generated through burning solid waste in a combined heat and power station. The average yield is around 2 MWh/t or 7.2 MJ/kg when the calorific value of waste is 9 MJ/kg (World Bank, 1999). Typically, the higher the waste heat value, the higher the output (World Bank, 1999). The heat value of composite material is around 30 MJ/kg, equivalent to three times that of ordinary municipal solid waste (Correia et al., 2011). Theoretically, composite waste should provide more heat and power in incineration, but it may not burn as easily as municipal solid waste. Halliwell states that output from incineration of sheet mould compound waste (typically glass fibre, resin and inert filler) is -0.4 MJ/kg (Halliwell, 2006). A WT blade contains up to 70 wt% glass fibre. Glass fibres are not combustible and will hinder incineration (Duflou et al., 2012). Glass fibre in the flue gas also disturbs the gas cleaning system, and the large amount of un-combusted fibre remaining at the end of the combustion process is also problematic (Schmidt, 2006). Currently there is no public incinerator which deals with composite waste in the UK (Liu, 2016). However, composite waste can be burnt in a cement kiln as part of an integrated process. In an operational composite incineration business run by Zajons and Holcim in Germany, composite WT blade waste is incinerated in a cement kiln. Each tonne of blade waste can replace 600 kg of coal fuel, equivalent to 4.16 GJ energy (Orenda Energy Solutions 2014; U.S. Energy Information Administration (EIA) 2017)). This figure is used in the base case calculation for incineration.

In choosing optimal technologies, we note that other factors may over-ride small differences in energy consumption. For example, incineration of municipal solid waste can reduce the final landfill volume by up to 95% (RenoSam&Ramboll, 2006), so enabling additional environmental benefit.

Ready-to-go/near ready-to-go recycling technologies include mechanical recycling, fluidised-bed recycling, pyrolysis recycling, and life extension. Mechanical recycling involves cutting the dismantled blade into pieces, then shredding and milling the waste into powder and fibre sections tens of millimetres in size. Howarth reports a mechanical recycling energy for composite waste of 0.27 MJ/kg when the feed rate is 150 kg/hr (Howarth et al., 2014). This finding has been supported by Pickering who reports a shredding energy consumption of 0.04 MJ/kg, a hammer milling energy consumption of 0.22 MJ/kg and a total energy consumption for the size reduction process for composite waste of 0.26 MJ/kg (Pickering et al., 2015). However, when the feed rate falls to 10 kg/hr, the average energy consumption rises to 2.03 MJ/kg as the machine standby energy consumption is high (Howarth et al., 2014). We adopt 0.27 MJ/kg in the model as a high feed rate is expected to be the norm when mechanical recycling is enlarged to industry scale.

The energy demand of the fluidised-bed process under optimal conditions has been determined to be around 10 MJ/kg of recycled CF (Meng, 2017; Meng et al., 2017a), but we note that when the feed rate is low this may rise to 15-30 MJ/kg (Pickering et al., 2015). The optimal energy demand for CFRP waste is therefore 9 MJ/kg using a fibrous product yield rate of 90%. The optimal energy demand for GFRP waste is 22.2 MJ/kg, using a fibrous product yield rate of 44% (Pickering et al., 2000).

The energy demand of pyrolysis is around 30 MJ/kg recyclate (Barnes, 2015; Witik et al., 2013). The solid yield rate is reported as 70.7% (Cunliffe et al., 2003). Based on this, the energy demand of pyrolysis becomes 21.2 MJ/kg FRP waste.

Life extension (LE) is the idea that blade lifespan is extended beyond that of the original design. This effectively reduces the number of blades that need to be manufactured, and reduces the total amount of end-of-life waste (Gamesa Corporación Tecnológica, 2015; Hazell, 2017; Wingerde and Nijssen, 2003). The feasibility of the concept has been demonstrated, and blade manufacturers and O&M service providers now provide this service (Beauson and Brøndsted, 2016; Natural Power, 2015; Sayer et al., 2009). However, when a product nears its designed end of life, the risk of developing widespread problems increases. Research from Gamesa supports this for WT blades, indicating that structural problems begin to arise, mainly in root connections and bonding, starting on blades of around 17-18 years old. Gamesa predicts these blades will have more problems as they approach and pass the designed service time (Gamesa Corporación Tecnológica, 2015). Based on this premise, we assume the O&M demand in the life extension period will be double that of the designed lifetime and that the environmental impact will also double. The life extension is set to 2 years, 5 years and 10 years for analysis. For example, the lifetime O&M energy consumption of the hybrid blade is 26.3 GJ (see Table 3). The annual O&M demand is assumed to double in the extension period, so the energy consumption is also doubled making it 26.3*2/20=2.63 GJ/year. The unit processing energy of a hybrid blade, for example, with a two-year life extension, is 2.63 GJ/year * 2 years * 1000 GJ to MJ / 7500 kg (average finished blade weight) = 0.7 MJ/kg. The LE process energies for the other two blade models and for 5 years and 10 years are calculated in the same way.

Lab-scale recycling technologies include MAP, chemical recycling and HVF. The MAP process involves microwave heating the material from the inside, saving energy compared to conventional pyrolysis. Its energy consumption is reported as 10 MJ/kg (Suzuki and Takahashi, 2005).

The two major chemical recycling technologies are hydrolysis and solvolysis, each of which has many mutations with different reaction temperatures, pressure, time and solvents

(Oliveux et al., 2015). The key process of chemical recycling is removing the polymer matrix of composites through chemical reaction. Several studies have looked at its energy consumption. The energy consumption used to dissolve a CFRP tennis racket is reported as being between 63 MJ/kg and 91 MJ/kg, and the higher the processing volume, the lower the unit energy consumption (Shibata and Nakagawa, 2014). For solvolysis of CFRP waste a range of process energies is reported, from 19.2 MJ/kg (Keith et al., 2016) to 101 MJ/kg (La Rosa et al., 2016). Keith's figure has been adopted for the base case since it is from a well-characterised experiment and came from real measurements rather than an estimation from modelled data as used by Shibata and Nakagawa (2014) and La Rosa (2016). The high-energy consumption cases are discussed in the sensitivity analysis below (Section 3.5). In the absence of GFRP chemical recycling energy data in the literature, we assume the energy consumption of chemical recycling to be the same for CFRP and GFRP.

The energy demand for optimally configured HVF to recycle composite waste is reported as 16.2 MJ/kg (Weh, 2012a). This number may vary over a wide range for different processing configurations which include the machine capacity, the number of pulses, and the voltage of pulses. The highest experimentally derived energy demand is reported as 43.2 MJ/kg (Weh, 2012a). Other research has found that when the composite waste is processed at 500 pulses, the resin residue is 40% and the energy consumption is 17.1 MJ/kg. If the pulses increase to 2000 the resin residue will reduce, but not significantly, while the energy consumption rises to 60 MJ/kg (Shuaib et al., 2016). We adopt 16.2 MJ/kg for the base case.

The unit processing energy of all EoL options are summarised in Table 4.

MJ/kg waste	**Full GF**	**Hybrid**	**Full CF**	**Source**
Landfill	0.26	0.26	0.26	(Li et al., 2016)
Incineration	-4.16	-4.16	-4.16	By author
Mechanical	0.27	0.27	0.27	(Howarth et al., 2014)
Fluidised-Bed Process	22.22	22.22 for GFRP waste 9.00 for CFRP waste	9.00	(Meng et al., 2017b; Pickering et al., 2015, 2000)
Pyrolysis	21.21	21.21	21.21	(Barnes, 2015; Cunliffe et al., 2003; Witik et al., 2013)
Microwave Assisted Pyrolysis	10.00	10.00	10.00	(Suzuki and Takahashi, 2005)
Chemical	19.20	19.20	19.20	(Keith et al., 2016)
High Voltage Fragmentation	16.20	16.20	16.20	(Weh, 2012b)

Life extension 2 years	0.55	0.70	1.40	By author
Life extension 5 years	1.37	1.75	3.49	By author
Life extension 10 years	2.73	3.50	6.99	By author

Table 4: Composite EoL option: base case energy requirement.

2.5 Recycling benefits

The outputs of composite recycling include energy, fibre, filler and resin. The actual recyclate product varies for each specific recycling process. Conventional landfill generates no recyclate. Incineration has the potential to recover heat energy while mechanical recycling, the fluidised-bed, pyrolysis, MAP and HVF recycling processes are able to reclaim fibre and filler. Chemical recycling can recover fibre and filler as well as resin. Life extension reduces new material usage which is equivalent to reclaiming energy. Recyclate products and energy are treated as the recycling benefits in this study.

The recycling benefits of the recyclate have been defined in Section 2.1 as being proportional to the tensile strength of the recyclate compared to the strength of virgin material. The tensile strength of recycled fibres found in the literature is summarised in Table 5. Where a technology has been reported by multiple sources, a median number has been taken.

EoL options	**Retained tensile strength of recycled fibre compared to virgin fibre**			
	GF		CF	
Mechanical	78%	(Palmer, 2009)	50%*	(Ogi et al., 2007)
Fluidised-bed process	50%	(Pickering et al., 2000)	75%	(Lester et al., 2004; Yip et al., 2002)
Pyrolysis	52%	(Cunliffe et al., 2003)	78%	(Onwudili et al., 2013)
Microwave Assisted Pyrolysis	52%**	n/a	80%	(Lester et al., 2004)
Chemical	58%	(Kao et al., 2012; Oliveux et al., 2012; Shyng and Ghita, 2013)	95%	(Jiang et al., 2009; Liu et al., 2009; Okajima et al., 2012)
High Voltage Fragmentation	88%	(Rouholamin et al., 2014)	83%***	(Weh, 2012a)

*Table 5: Recycled fibre retained tensile strength compared to virgin fibre. *Significant fibre damage has been stated, but no data has been found. This data is estimated by the authors. **No reference found, estimated to be the same as conventional pyrolysis as the processing conditions are similar. *** No fibre strength has been found directly from the literature. Estimated to be the same ratio as the strength of a rotorcraft door hinge made with recycled CF compared to a virgin hinge..*

A further factor is that the lengths of the recycled fibres vary and the recycled fibres have different amounts of resin residue; consequently, the fibres are not as clean and homogeneous as virgin fibre and thus require post-processing (Meng, 2017). Very limited data is yet available to indicate how much work is needed. We have deducted 10% of the recyclate value from the final recycling benefits to take this into account.

As well as the recyclate benefits of recycled fibre, the recyclate benefits of the resin and fillers need to be determined. Previous studies have identified that the resin in composite can be recycled through chemical processes and have proposed that this recycled resin can be reused, but none have indicated either the yield rate or the performance of recycled resin (Bai et al., 2010; Keith et al., 2016; Oliveux et al., 2015). Here we conservatively assume the recycled resin impact value is 50% of new resin. The fillers recovered can be used to substitute for $CaCO_3$ (Pickering, 2006) but information is limited. Since the impact value of $CaCO_3$ is low, less than 0.5 MJ/kg (De and White, 2001), fillers have been excluded from benefits calculations. For comparison purposes, all the recycled fibre, filler and resin have been converted to equivalent energy values in the recycling benefits estimation.

The overall recyclate benefits are calculated by combining the unit recycling benefits with the recycling yield rate. Fibrous material yield rates by weight from the literature are included in Table 6. No data for MAP has been found. As the mechanism of the MAP process is close to that of conventional pyrolysis, we assume the yield rate of fibrous product from MAP is the same as for conventional pyrolysis, namely 70%. The yield rate of recycled resin is assumed to be 100% (Keith, 2017).

All the blade waste recycling processes need at least one, but often multiple stages of size reduction beforehand. Typically, some material is lost during these stages. No figures have been found in the literature. We conservatively assume that 5% of all materials (fibre and resin) is lost for all recycling processes and this is included to obtain final yield rates for each recycling process (Table 6).

	Lost during size reduction preparation	**Fibrous recyclate yield rate**	**Final yield rate**	**Source**
Mechanical	5%	58%	55%	Palmer 2009
Fluidised Bed GF		44%	42%	Pickering 2000
Fluidised Bed CF		90%	86%	Meng 2017
Pyrolysis and Microwave Assisted Pyrolysis		70%	67%	Cunliffe 2003

Chemical		100%	95%	Keith 2016
High Voltage Fragmentation		60%	57%	Weh 2012

Table 6: Fibrous product yield rates for different recycling processes.

2.6 Environmental impact model development

The environmental impact model is constructed and calculated as follows:

- Net impact of a WT blade = Lifetime impact + EoL impact + Recycling benefits
- Lifetime impact = manufacture impact (materials and processing from BoM) + transportation impact (wind farm to recycling facility) + O&M impact (material + workers' transportation)
- EoL impact = unit recycling processing energy (MJ/kg) * the amount of waste processed (kg)
- Recyclate/recycling benefits = -((virgin fibre embodied energy * recycled fibre performance * fibre yield rate * (100% - post process energy) + (virgin resin embodied energy * recycled resin performance * resin yield rate))* (100% - overall processing lost)
- The recycled fibre performance is defined as the ratio of the tensile strength of recycled fibre to that of the virgin fibre.
- For example (chemical recycling for the GF blade): Virgin resin energy = 312.1 GJ; virgin fibre energy = 237.1 GJ.
  Recyclate benefits = -(237.1*58%*100%*(100%-10%)+(312.1*50%*100%)*(100%-5%) = -265.8 GJ

3 Results and discussion

3.1 Full GF blade

In Figure 2, the blue bars represent the lifetime environmental impact comprising the impacts of manufacture, O&M and transportation. The orange bars represent the impact of EoL processes. The grey bars present recyclate/recycling benefits. We use positive values to represent the energy consumption. Since the recycling benefit represents the equivalent energy reclaimed, it has a negative value. By adding the lifetime impact to the EoL process impact and recycling benefit, the net environmental impact is obtained. Then the net impacts of each EoL process are compared with the 'no processing' option, landfill, as a benchmark, shown by the blue line.

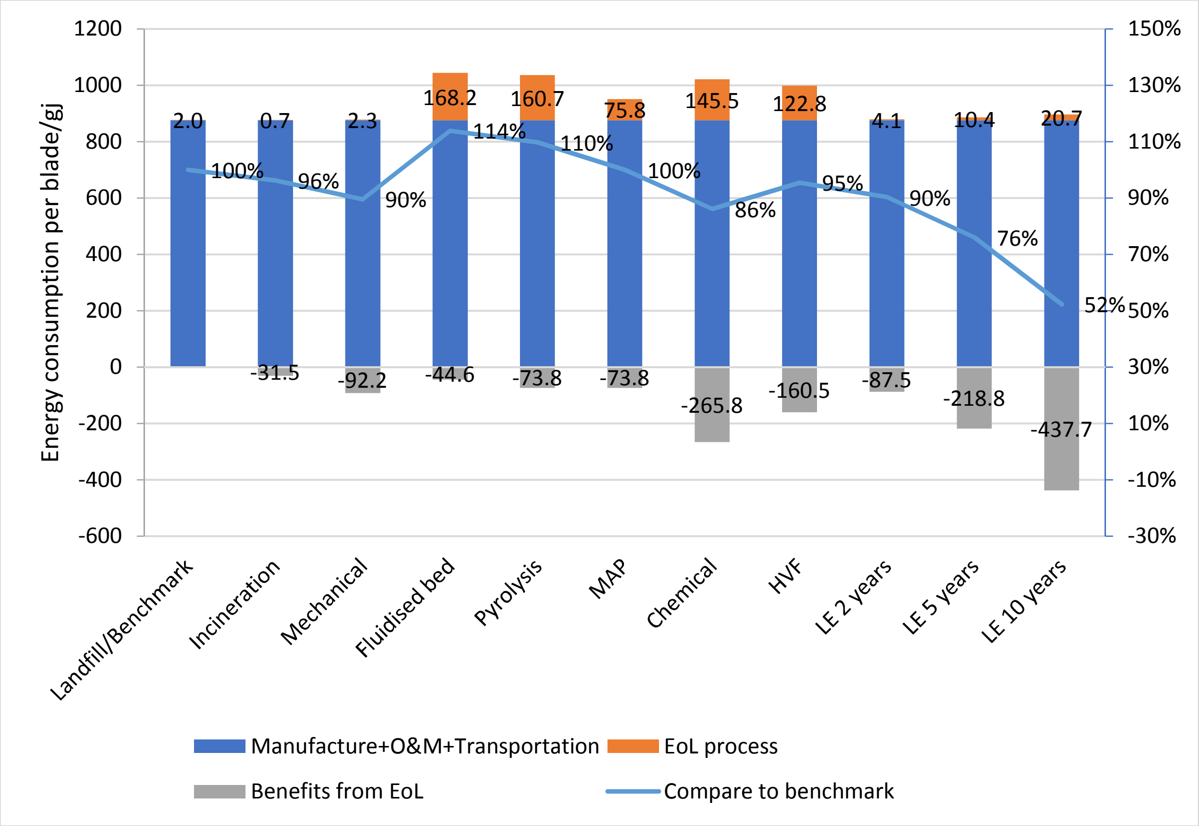

Figure 2: Full glass fibre blade net impacts of waste treatment options (incineration, mechanical, fluidised bed, pyrolysis, MAP, chemical, and HVF processes) and life extension for 2, 5 and 10 years compared to conventional landfill as the benchmark process. MAP=Microwave Assisted Pyrolysis, HVF=High Voltage Fragmentation, LE=life extension.

The highest impacts are found for the fluidised-bed and pyrolysis processes because of their high recycling energy consumption and low recyclate value. The net impacts of mechanical recycling, incineration, chemical recycling, HVF and two-year life extension (LE) are between 86% and 95% of the net impact of landfill, so providing only marginal reduction in environmental impact. The conclusion from this analysis is therefore that there is little potential for significant environmental impact reduction from such EoL processes. Environmental impact reduction must be a weak driver for moving away from landfill: any impetus will depend more on the other aspects of the recycling operation such as environmental protection regulations and financial performance. However, non-recycling options are more promising: LE 5 years and LE 10 years perform better and can significantly reduce the net impacts to 76% and 52% of those of landfill, respectively. The risk of blade failure must increase the longer the blade is used after the designed lifetime, but LE is actively being assessed commercially.

3.2 Hybrid blade

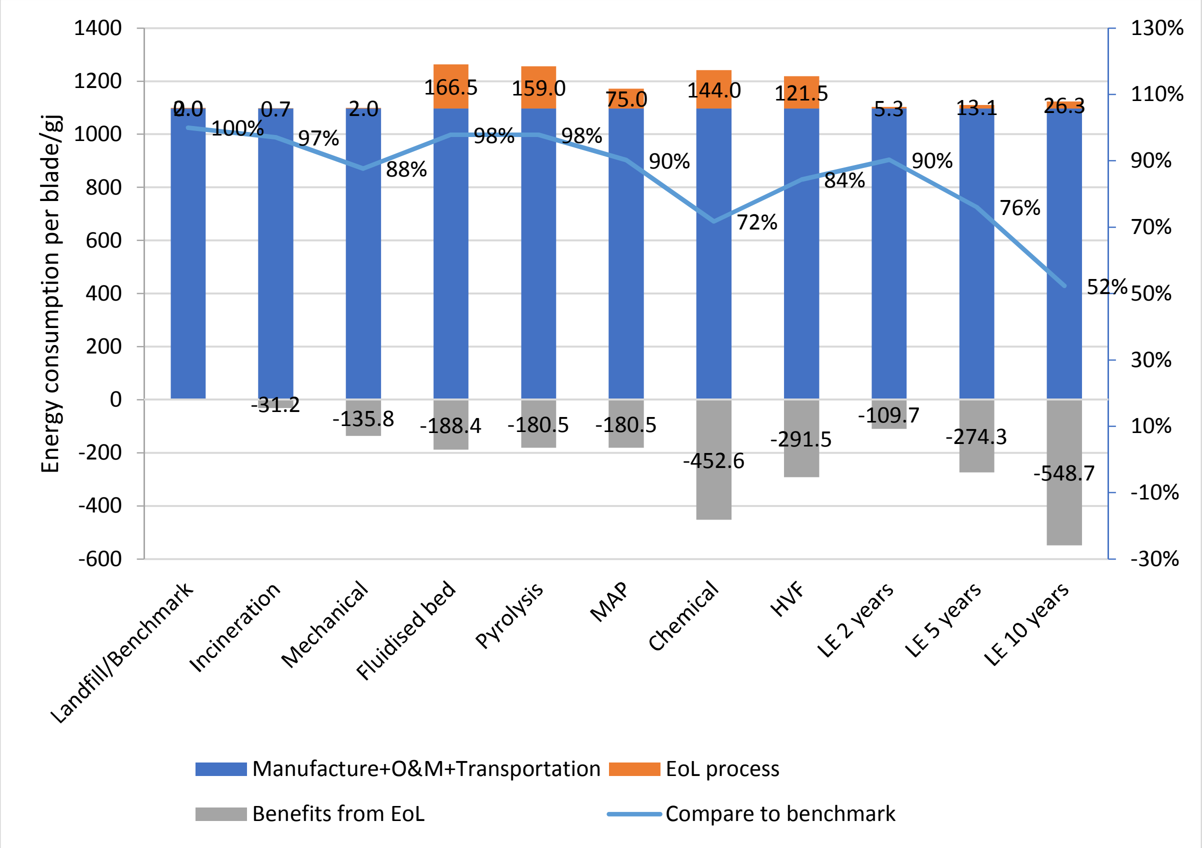

Figure 3: Hybrid blade net impacts of waste treatment options (incineration, mechanical, fluidised bed, pyrolysis, MAP, chemical, and HVF processes) and life extension for 2, 5 and 10 years compared to conventional landfill as the benchmark process. MAP=Microwave Assisted Pyrolysis, HVF=High Voltage Fragmentation, LE=life extension.

Turning to the hybrid blade, the recyclate benefits for most EoL options are improved in comparison to the full GF blade, as part of the recyclate is the high-value, high-energy-intensive CF. The net impacts of pyrolysis and fluidised-bed process are still the highest, at 98% compared to landfill. The incineration impact, however, increases to 97%. Although the CF releases some incineration energy, its manufacture stage is very energy-intensive so the beneficial effect of energy recovered from the incineration process is small by comparison. The impact of mechanical recycling, MAP, HVF and LE 2 years are in the range of 84% to 90% which are slightly reduced compared to the results for the GF blade. Chemical recycling shows the most promise here, and can reduce the net impact to 72% of landfill, less than that of LE 5 years but still exceeding that of LE 10 years.

3.3 Full CF blade

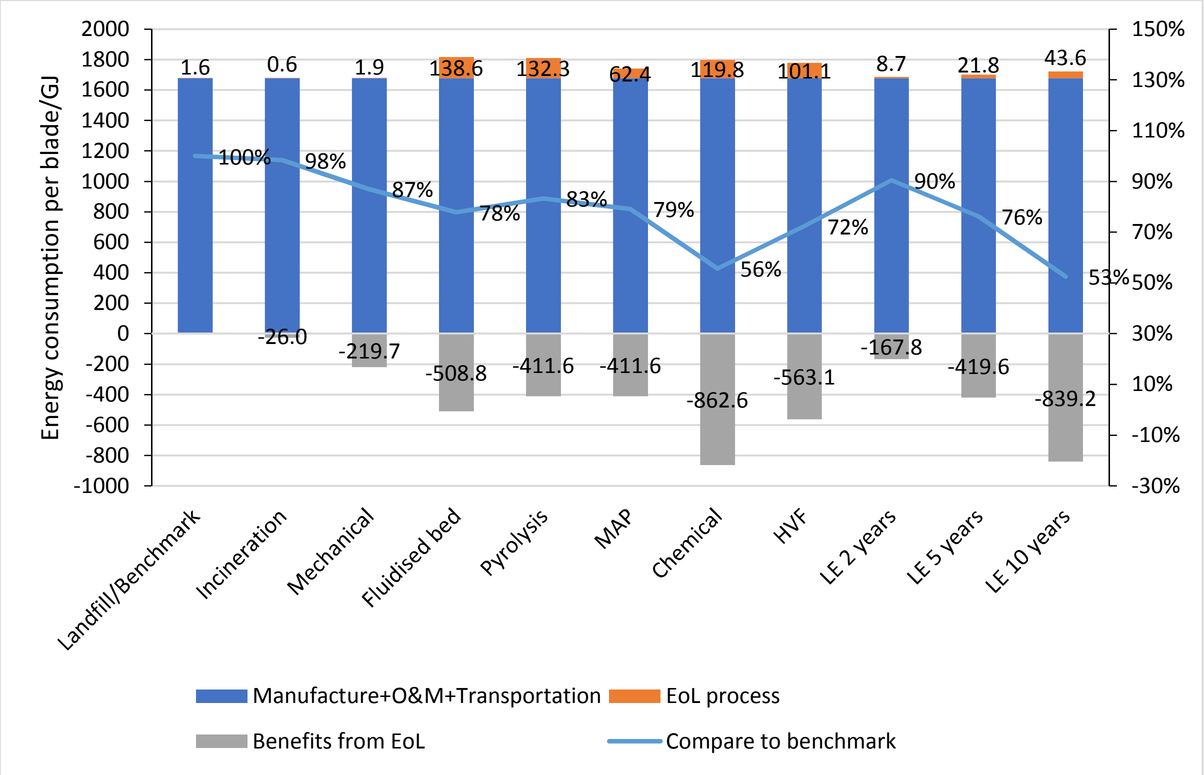

Figure 4: Full carbon fibre blade net impacts of waste treatment options (incineration, mechanical, fluidised bed, pyrolysis, MAP, chemical, and HVF processes) and life extension for 2, 5 and 10 years compared to conventional landfill as the benchmark process. MAP=Microwave Assisted Pyrolysis, HVF=High Voltage Fragmentation, LE=life extension.

The manufacturing energy consumption of virgin CF is 286 MJ/kg which is 4.5 times higher than for GF and 1.2 times higher than for epoxy resin. For the CF blades, the EoL options that can reclaim CF with less fibre performance damage are more favourable as higher recyclate values will be attained. The energy consumption of the EoL processes is a smaller part of the total impact and so has less effect. The least competitive process for CF blades is incineration, which has 98% of the impact of landfill. The ready-to-go technologies such as the fluidised-bed and pyrolysis processes can reduce the impact to around 80%. More advanced processes like HVF can significantly reduce the net impacts to 72%. Chemical recycling provides the best result among the recycling options with only 56% net impact compared to landfill. This is just 3% higher than the impact of LE 10 years.

3.4 Sensitivity analysis

In the following analysis, the effect of variations in EoL impact and recycling benefit on net lifetime impact are assessed. The EoL impact data is represented as range bars, using the full range of data from the literature (discussed in Section 2.4). Where the literature is limited or there is only a single data source (fluidised-bed, pyrolysis, microwave assisted pyrolysis (MAP) and lifetime extension) processing energies are varied by +/- 20% in order to test sensitivity.

The recyclate benefit, defined as a combination of yield rate and quality or value of the recyclate, is varied theoretically taking values between -100% (zero recyclate benefit) and +100% (double the base case benefit). The net environmental impact is then plotted against recyclate benefit variation. The environmental impact decreases as the recycling benefit increases, so processes may shift from being unfavourable (positive impact) to favourable (negative impact); the crossover points are indicated for such processes (see Figures 6, 8 and 10). This analysis provides useful guidance on where it is worth devoting effort to EoL process improvement. The results are presented in Figures 5-10 for the three blade types.

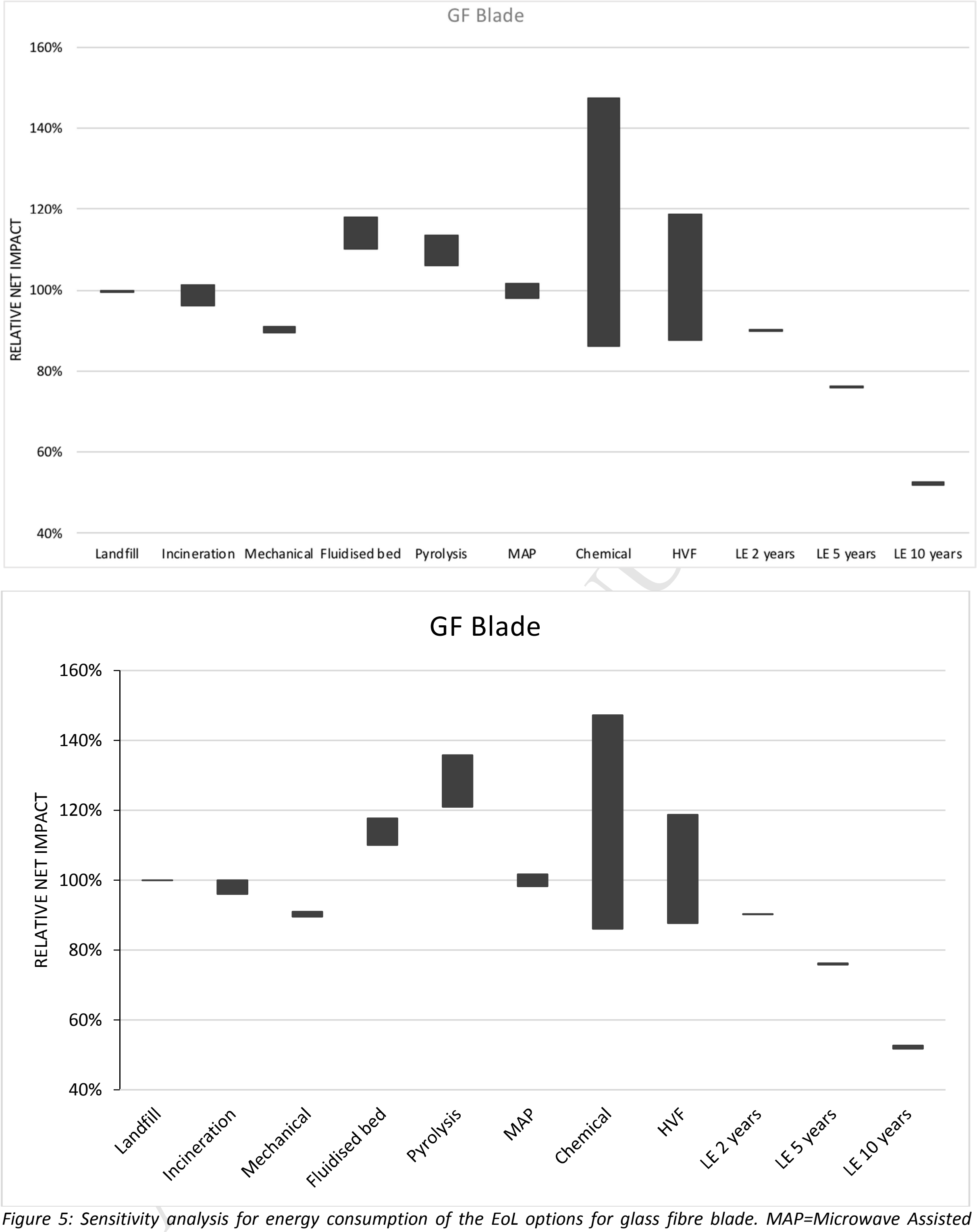

Figure 5: Sensitivity analysis for energy consumption of the EoL options for glass fibre blade. MAP=Microwave Assisted Pyrolysis, HVF=High Voltage Fragmentation, LE=life extension. The most environmentally favourable processes have the most negative impact.

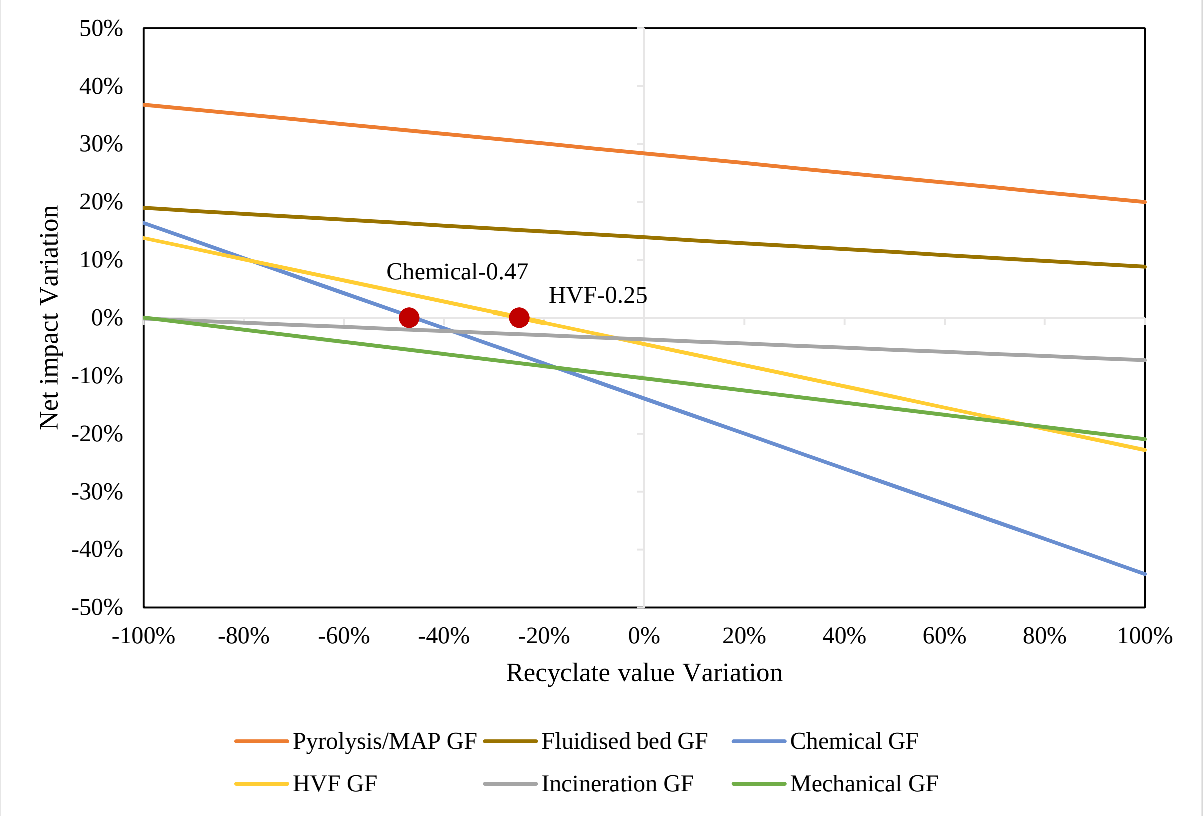

Figure 6: Sensitivity of net impact of GF blade as a function of the recyclate benefit. MAP=Microwave Assisted Pyrolysis, HVF=High Voltage Fragmentation, LE=life extension.

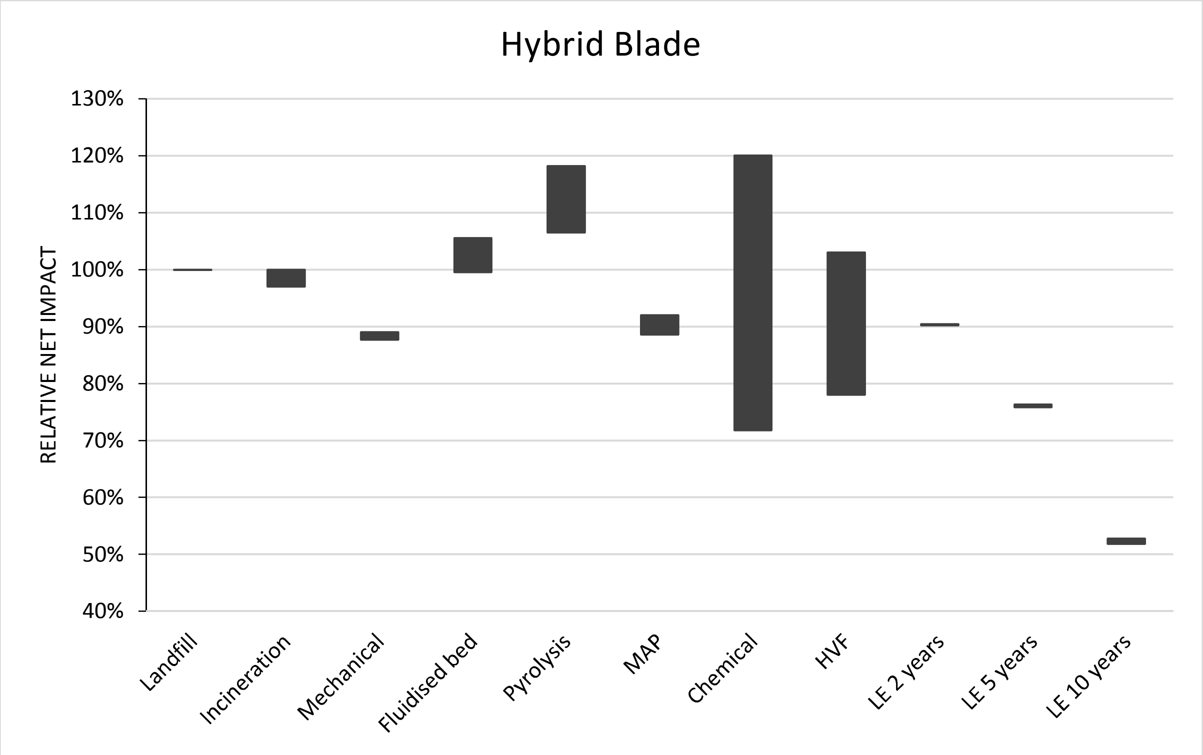

Figure 7: Sensitivity analysis for energy consumption of the EoL options for hybrid blade. MAP=Microwave Assisted Pyrolysis, HVF=High Voltage Fragmentation, LE=life extension.

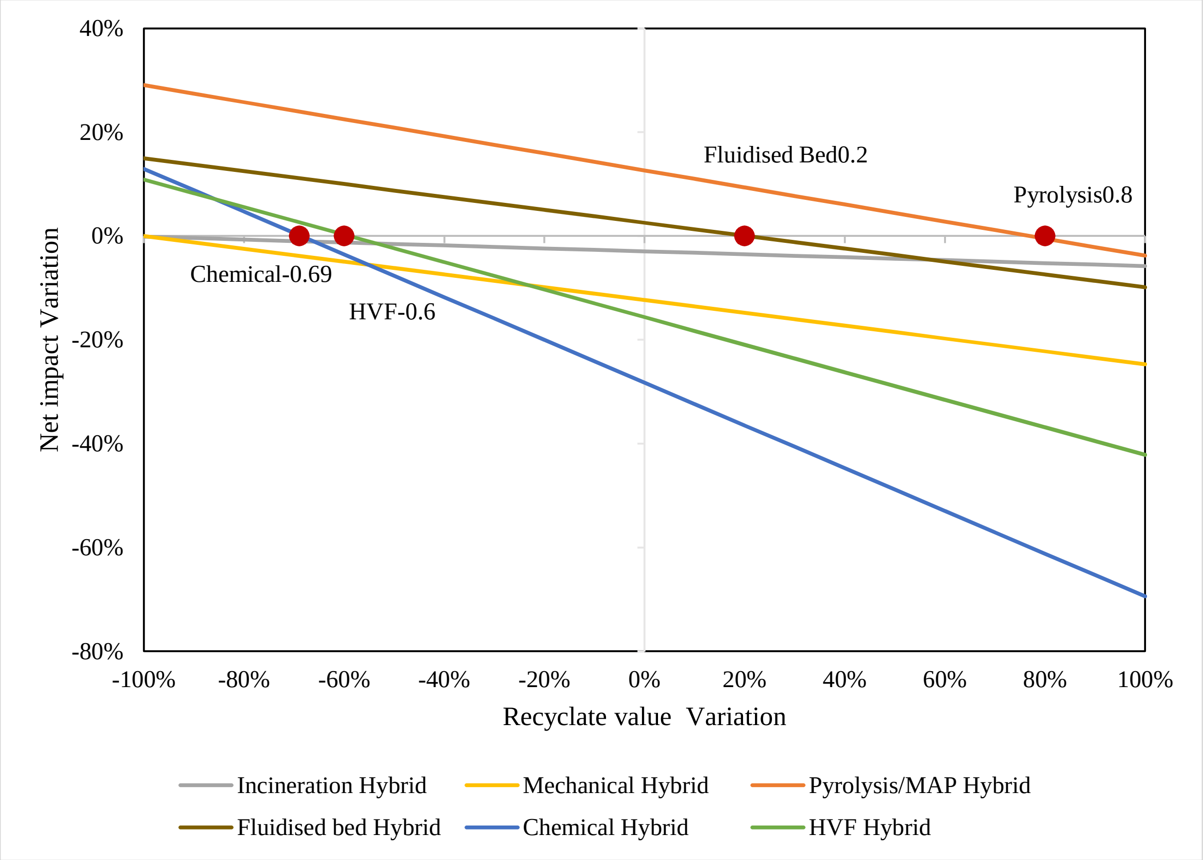

Figure 8: Sensitivity of net impact of hybrid blade as a function of the recyclate benefit. MAP=Microwave Assisted Pyrolysis, HVF=High Voltage Fragmentation, LE=life extension.

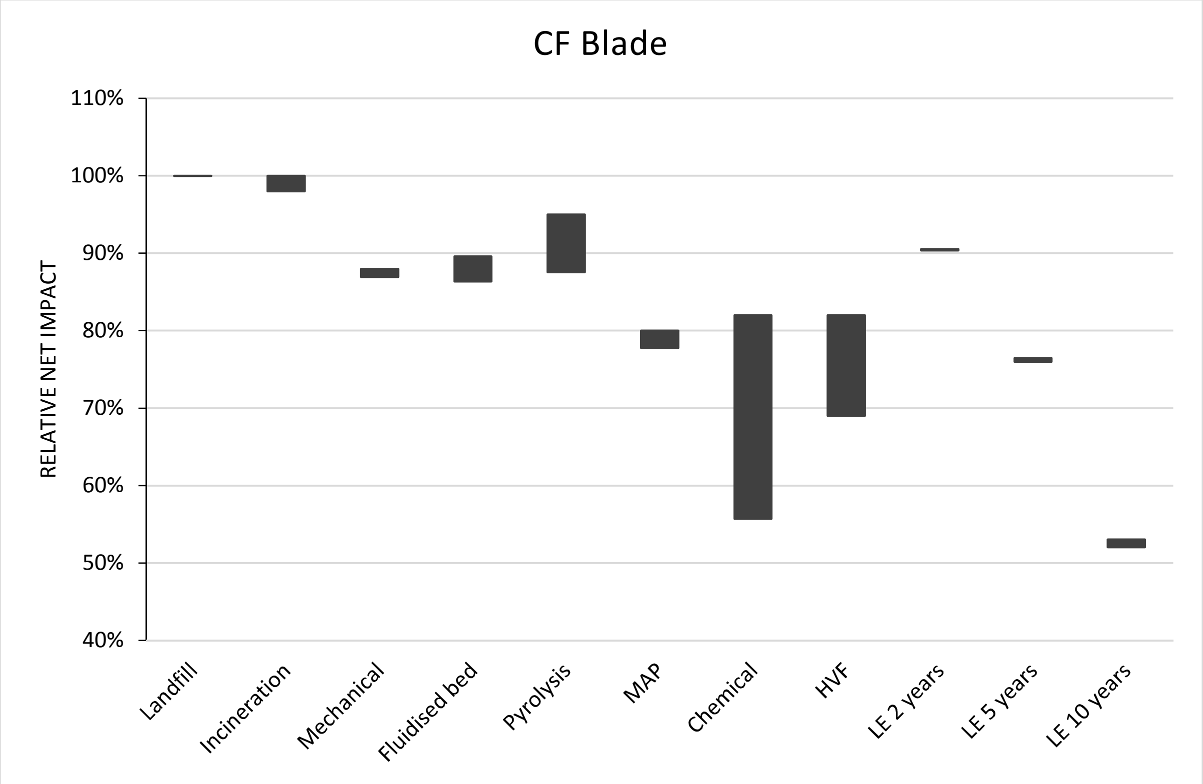

Figure 9: Sensitivity analysis for energy consumption of the EoL options for carbon fibre blade. MAP=Microwave Assisted Pyrolysis, HVF=High Voltage Fragmentation, LE=life extension.

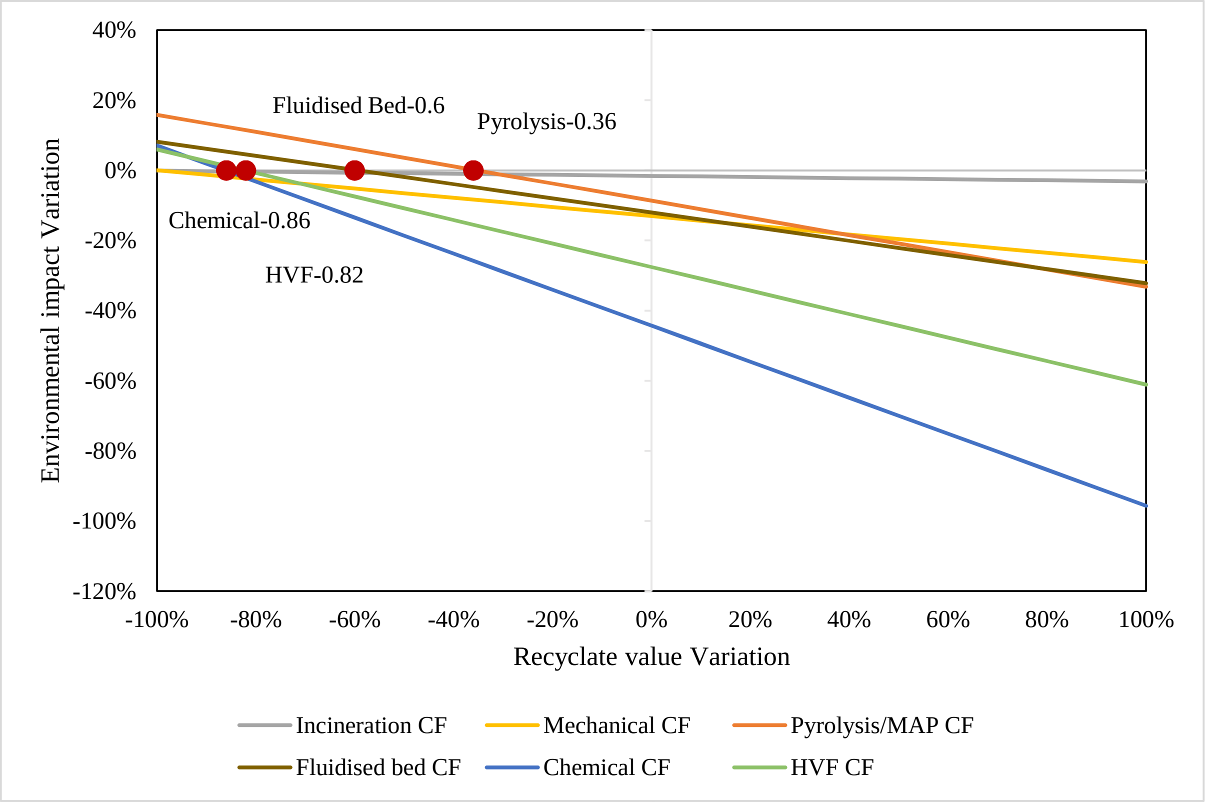

Figure 10: Sensitivity of net impact of CF blade as a function of recyclate benefit. MAP=Microwave Assisted Pyrolysis, HVF=High Voltage Fragmentation, LE=life extension.

The results reveal that variations in the EoL processing energy make more of a difference to the viability of recycling the GF blade (Figure 5) compared to other blade types (Figures 7 and 9). The high energy processes (fluidised-bed and pyrolysis) are high environmental impact because they always require high energy input; low processing energy technologies (mechanical recycling and incineration) are always favourable. Only chemical recycling and HVF are affected significantly by variation in process energy to the extent that they can cross the breakeven point. This reveals that further investigation of data for processing energy and recyclate benefit for these two technologies would be worthwhile.

For the CF blade, the variation of recyclate benefit has an insignificant effect on whether it is worth recycling or not, in terms of energy. This is because the recycling potential of the CF blade is high and the recycling processing energy consumption is minor in comparison, so even if the recyclate benefit is considerably reduced, the net impact is still lower than that of landfill. The hybrid blade unsurprisingly sits in the middle and the breakeven point is more sensitive than the other two blades to recyclate benefit variation. Reliable recyclate benefits are important for the hybrid blade to determine the ‘optimal’ EoL option.

3.5 Discussion

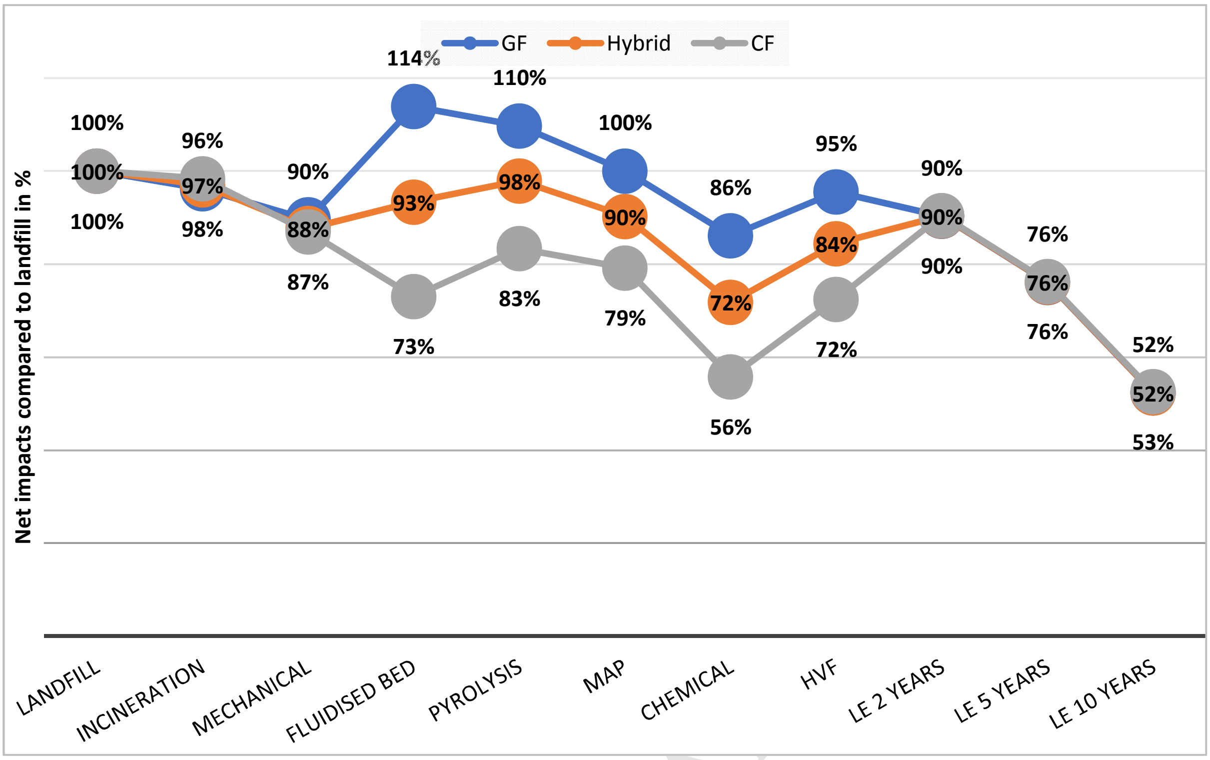

Figure 11: EoL options comparison of net impacts of three blade models (i.e., GF, hybrid and CF) to benchmark landfill. MAP=Microwave Assisted Pyrolysis, HVF=High Voltage Fragmentation, LE=life extension.

Using energy consumption as the metric, the net lifecycle environmental impacts of the three blade models in the base case are summarised here for comparison. As shown in Figure 11, for the GF blade the results of ready-to-go (the fluidised-bed process, pyrolysis) and lab scale (MAP, chemical, HVF) recycling technologies are not encouraging. The combination of high processing energy and low recyclate value means most have higher net impacts than landfill, and the benefits are insignificant even for those with lower net impacts. Of all recycling options, chemical recycling (if available on a commercial scale) will be best placed to reduce environmental impact to 86% of the landfill impact. On the other hand, if we want to process the waste now rather than wait for technological development, mechanical recycling is the 'optimal' mature technology as it can reduce net impact to 90% of the landfill impact. Incineration is another possibility to be considered: although the net impact is reduced only to 96%, it has the added benefit of significantly reducing residual waste volumes.

Considering all EoL options, life extension (LE) 10 years has the lowest net impact, the best overall result, reducing the net impact to 53%. Hence, at current technological levels, life extension is the 'optimal' EoL option for GF blades. These life-extended blades will ultimately still need to be processed, although this option gives more time for lab-scale technologies to mature, with the possibility of lower processing energy and better recyclate performance in the future.

In the future, when the lab-scale technologies are mature, chemical recycling would be the 'optimal' choice since it has the best potential to reduce the maximum environmental impact. However, it should be noted that this option is strongly affected by the EoL processing energy and the recyclate value, both of which may change in the future. If the processing energy increases to over 35 MJ/kg or the recyclate value drops by 47% (Section 3.4, Figure 6), it is no longer worth using chemical recycling to reduce environmental impact.

For the hybrid blade, mechanical recycling and incineration are the only two methods which have a lower impact than landfill from among the conventional and ready-to-go EoL options. These methods can reduce the net impact to 88% and 97% respectively. The more advanced lab-scale MAP and HVF can reduce the impact to 90% and 84% respectively. Chemical recycling performs the best and can provide a significant decrease in the net impact to 72%. Sensitivity analysis shows that net impact is strongly dependent on the recyclate value and processing energy. Therefore, the choice of 'optimal' EoL option for hybrid blades is reliant on very accurate data, which will change as technologies develop and scale up.

The high embodied energy of CF blades makes their recycling potential higher than the other two blades: the impact of every EoL option is lower than landfill in the base case and it is less sensitive to variation in processing energy and recyclate value. Conventional mechanical recycling can reduce the impact to 87%. The ready-to-go technologies can reduce the impact to 73%. The advanced lab-scale technologies all show promise for reducing impact, the best being chemical recycling with the potential to reduce the net environmental impact of the CF blade to 56% compared to landfill. However, it should be noted that there is considerable data scatter for these lab-scale technologies (Section 3.4), so there is some uncertainty around this figure. Since all EoL options are able to reduce the net impact, albeit by different magnitudes, the 'optimal' EoL option would be decided by other factors such as technology readiness or economic performance.

4 Conclusions

In this paper we have adopted an eco-audit approach, using energy as the measure of environmental impact to compare EoL options for WT blades. The most environmentally favourable process is dependent on the materials used for the blades (GF or CF). The extent to which process improvement might affect the viability of different EoL processes has been assessed by looking at 'crossover' points when the environmental impact becomes favourable. This analysis provides guidance on promising research areas, indicating where significant EoL environmental benefits could derive from process improvements. Environmental impact is only one aspect of the WT blade end-of-life problem. In the actual implementation of waste processing, many additional issues need to be considered, such as the recycling cost, differences between regions, technology readiness levels, the state of the market, and policy. Nevertheless, increased global awareness of environmental matters means that this will increasingly feature in the choice of appropriate EoL options for the growing volume of post-service wind turbine blades. This study thus plays a crucial role in identifying suitable waste management strategies to address the emerging waste burden of end-of-life wind turbine blades in terms of minimising the environmental impact and ultimately to formulate guidelines on this problem to aid industry and policy makers.

In summary, the optimal end-of-life treatments for the three types of WT blades based on the net environmental impact are as follows:

- GF blade: mechanical for recycling at this moment, life extension for non-processing; chemical for recycling in the future.
- Hybrid blade: mechanical for recycling at this moment, chemical for recycling in the future.
- CF blade: fluidised bed for recycling at this moment, chemical for recycling in the future.

Notes

Declarations of interest: none.

Acknowledgements

The authors would like to thank the Industrial Sustainability Research Group at the University of Cambridge and the industrial cooperation partners for advice and support. This work was supported, in part, by China Scholarship Council (CSC). The authors are also grateful to Jesus College, Cambridge for financial support.

Nomenclature

GF	Glass fibre
CF	Carbon fibre
GFRP	Glass fibre reinforced plastic
CFRP	Carbon fibre reinforced plastic
WT	Wind turbine
EoL	End of life
O&M	Operation and maintenance
MAP	Microwave assisted pyrolysis
HVF	High voltage fragmentation

LE	Life extension
LCA	Life cycle assessment

5 References

Andersen, P.D., Bonou, A., Beauson, J., Brønsted, P., 2014. Recycling of wind turbines, DTU International Energy Report 2014.

Ashby, M., Coulter, P., Ball, N., Bream, C., 2009. The CES EduPack Eco Audit Tool - A White Paper.

Ashby, M.F., 2009. Materials and the Environment : Eco-informed Material Choice. Butterworth-Heinemann, Burlington.

Bai, Y., Wang, Z., Feng, L., 2010. Chemical recycling of carbon fibers reinforced epoxy resin composites in oxygen in supercritical water. Mater. Des. 31, 999–1002. https://doi.org/10.1016/j.matdes.2009.07.057

Barnes, F., 2015. Presentation: Commercial Aspects of Carbon Fibre Recycling by ELG Carbon Fibre Ltd., in: GO Carbon FIbre Recycling 2015. ELG Carbon Fibre Ltd., Manchester.

Beauson, J., Bech, J.I., Brøndsted, P., 2013. Composite recycling : Characterizing end of life wind turbine blade materials, in: The 19th International Conference on Composite Materials. Montreal, Canada, p. 8.

Beauson, J., Brøndsted, P., 2016. Wind Turbine Blades: An End of Life Perspective, in: Ostachowicz, W. (Ed.), MARE-WINT. Springer, pp. 421–432. https://doi.org/10.1007/978-3-319-39095-6

Brøndsted, P., Lilholt, H., Lystrup, A., 2005. Composite Materials for Wind Power Turbine Blades. Annu. Rev. Mater. Res. 35, 505–538. https://doi.org/10.1146/annurev.matsci.35.100303.110641

Corona, A., 2015. Comparative Environmental Sustainability Assessment of Bio-Based Fibre Reinforcement Materials for Wind Turbine Blades. Wind Eng. 39, 53–64.

Corona, A., 2013. Quantitative sustainability assessment of bio-based materials for wind turbine rotor blades (Thesis). Technical University of Denmark.

Correia, J.R., Almeida, N.M., Figueira, J.R., 2011. Recycling of FRP composites: reusing fine GFRP waste in concrete mixtures. J. Clean. Prod. 19, 1745–1753. https://doi.org/10.1016/j.jclepro.2011.05.018

Cunliffe, A.M., Jones, N., Williams, P.T., 2003. Pyrolysis of composite plastic waste. Environ. Technol. 24, 653–663. https://doi.org/10.1080/09593330309385599

De, S.K., White, J.R., 2001. Rubber technologist's handbook, Volume 1. ed. iSmithers Rapra Publishing.

Duflou, J.R., Deng, Y., Van Acker, K., Dewulf, W., 2012. Do fiber-reinforced polymer composites provide environmentally benign alternatives? A life-cycle-assessment-based study. MRS Bull. 37, 374–382. https://doi.org/10.1557/mrs.2012.33

EWEA, 2014. Wind energy scenarios for 2020 [WWW Document]. URL http://www.ewea.org/fileadmin/files/library/publications/scenarios/EWEA-Wind-energy-scenarios-2020.pdf (accessed 11.12.14).

Gamesa Corporación Tecnológica, 2015. Gamesa Life Extension Program, in: European Wind Energy Association Conference 2015. EWEA, Paris.

Granta Design, 2016. Eco-data in CES Eco-Selector 2016 database.

GWEC, 2016. Global Wind Report 2015: Annual market update [WWW Document]. Wind energy Technol. URL http://www.gwec.net/global-figures/wind-energy-global-status/

(accessed 6.9.16).

Halliwell, S., 2010. FRPs - The environmental agenda. Adv. Struct. Eng. 13, 783–791. https://doi.org/10.1260/1369-4332.13.5.783

Halliwell, S., 2006. End of Life Options for Composite Waste: Recycle, Reuse or Dispose?

Hannah, R., Max, R., 2017. Energy Production & Changing Energy Sources [WWW Document]. Ourworlddata.org website. URL https://ourworldindata.org/energy-production-and-changing-energy-sources (accessed 12.2.17).

Hazell, J., 2017. Developing a circular economy for novel materials. London.

Holmes, M., 2014. Global carbon fibre market remains on upward trend. Reinf. Plast. 58, 38–45. https://doi.org/10.1016/S0034-3617(14)70251-6

Howarth, J., Mareddy, S.S.R., Mativenga, P.T., 2014. Energy intensity and environmental analysis of mechanical recycling of carbon fibre composite. J. Clean. Prod. 81, 46–50. https://doi.org/10.1016/j.jclepro.2014.06.023

Jagadish, P.R., Khalid, M., Li, L.P., Hajibeigy, M.T., Amin, N., Walvekar, R., Chan, A., 2018. Cost effective thermoelectric composites from recycled carbon fibre: From waste to energy. J. Clean. Prod. 195, 1015–1025. https://doi.org/10.1016/j.jclepro.2018.05.238

Jiang, G., Pickering, S., Lester, E., Turner, T., Wong, K., Warrior, N., 2009. Characterisation of carbon fibres recycled from carbon fibre/epoxy resin composites using supercritical n-propanol. Compos. Sci. Technol. 69, 192–198. https://doi.org/10.1016/j.compscitech.2008.10.007

Job, S., 2014. Recycling composites commercially. Reinf. Plast. 58, 32-34,36-38. https://doi.org/10.1016/S0034-3617(14)70213-9

Job, S., Leeke, G., Mativenga, P.T., Oliveux, G., Pickering, S., Shuaib, N.A., 2016. COMPOSITES RECYCLING : Where are we now ?

Kao, C.C., Ghita, O.R., Hallam, K.R., Heard, P.J., Evans, K.E., 2012. Mechanical studies of single glass fibres recycled from hydrolysis process using sub-critical water. Compos. Part A Appl. Sci. Manuf. 43, 398–406. https://doi.org/10.1016/j.compositesa.2011.11.011

Keith, M., 2017. PhD student working on solvolysis for recycling carbon fibre reinforced composites from University of Birmingham.

Keith, M., Oliveux, G., Leeke, G.A., 2016. Optimisation of Solvolysis for Recycling Carbon Fibre Reinforced composites. ECCM17 - 17th Eur. Conf. Compos. Mater. 26–30.

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. Part B Eng. 104, 17–25. https://doi.org/10.1016/j.compositesb.2016.08.015

Larsen, K., 2009. Recycling wind turbine blades. Renew. Energy Focus 9, 70–73. https://doi.org/10.1016/S1755-0084(09)70045-6

Lester, E., Kingman, S., Wong, K.H., Rudd, C., Pickering, S., Hilal, N., 2004. Microwave heating as a means for carbon fibre recovery from polymer composites: a technical feasibility study. Mater. Res. Bull. 39, 1549–1556. https://doi.org/10.1016/j.materresbull.2004.04.031

Li, X., Bai, R., McKechnie, J., 2016. Environmental and financial performance of mechanical recycling of carbon fibre reinforced polymers and comparison with conventional disposal routes. J. Clean. Prod. 127, 451–460. https://doi.org/10.1016/j.jclepro.2016.03.139

Liu, P., 2016. Site visit in Amey Cespa Waterbeach, Info about landfill and incineration cost in UK heared from Principal Operations Manager.

Liu, P., Barlow, C., 2016. The environmental impact of wind turbine blades. IOP Conf. Ser. Mater. Sci. Eng. 139, 012032. https://doi.org/10.1088/1757-899X/139/1/012032

Liu, P., Barlow, C.Y., 2017. Wind turbine blade waste in 2050. Waste Manag. https://doi.org/10.1016/j.wasman.2017.02.007

Liu, W., 2014. CTO of LZFRP, Personal Communication.

Liu, Y., Shan, G., Meng, L., 2009. Recycling of carbon fibre reinforced composites using water in subcritical conditions. Mater. Sci. Eng. A 520, 179–183. https://doi.org/10.1016/j.msea.2009.05.030

Marsh, G., 2010. Could thermoplastics be the answer for utility-scale wind turbine blades? Reinf. Plast. 54, 31–35. https://doi.org/10.1016/S0034-3617(10)70029-1

McKenna, R., Ostman V.d. Leye, P., Fichtner, W., 2016. Key challenges and prospects for large wind turbines. Renew. Sustain. Energy Rev. 53, 1212–1221. https://doi.org/10.1016/j.rser.2015.09.080

Meng, F., 2017. PhD student, working on the fludised bed project from University of Nottingham, Email and face to face commnunication.

Meng, F., McKechnie, J., Turner, T., Wong, K.H., Pickering, S.J., 2017a. Environmental Aspects of Use of Recycled Carbon Fiber Composites in Automotive Applications. Environ. Sci. Technol. 51, 12727–12736. https://doi.org/10.1021/acs.est.7b04069

Meng, F., McKechnie, J., Turner, T.A., Pickering, S.J., 2017b. Energy and environmental assessment and reuse of fluidised bed recycled carbon fibres. Compos. Part A Appl. Sci. Manuf. 100, 206–214. https://doi.org/10.1016/j.compositesa.2017.05.008

Meng, F., Olivetti, E.A., Zhao, Y., Chang, J.C., Pickering, S.J., McKechnie, J., 2018. Comparing Life Cycle Energy and Global Warming Potential of Carbon Fiber Composite Recycling Technologies and Waste Management Options. ACS Sustain. Chem. Eng. 6, 9854–9865. https://doi.org/10.1021/acssuschemeng.8b01026

Naqvi, S.R., Prabhakara, H.M., Bramer, E.A., Dierkes, W., Akkerman, R., Brem, G., 2018. A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy. Resour. Conserv. Recycl. 136, 118–129. https://doi.org/10.1016/j.resconrec.2018.04.013

Natural Power, 2015. Re-Powering, Up-Powering & Life Extension.

Nemry, F., Leduc, G., Mongelli, I., Uihlein, A., 2008. Environmental Improvement of Passenger Cars (IMPRO-car). https://doi.org/10.2791/63451

Ogi, K., Nishikawa, T., Okano, Y., Taketa, I., 2007. Mechanical properties of ABS resin reinforced with recycled CFRP. Adv. Compos. Mater. 16, 181–194. https://doi.org/10.1163/156855107780918982

Okajima, I., Watanabe, K., Sako, T., 2012. Chemical Recycling of Carbon Fiber Reinforced Plastic with Supercritical Alcohol. J. Adv. Res. Phys. 3, 1–4.

Oliveux, G., Bailleul, J.-L., Salle, E.L.G. La, 2012. Chemical recycling of glass fibre reinforced composites using subcritical water. Compos. Part A Appl. Sci. Manuf. 43, 1809–1818. https://doi.org/10.1016/j.compositesa.2012.06.008

Oliveux, G., Dandy, L.O., Leeke, G. a., 2015. Current Status of Recycling of Fibre Reinforced Polymers: review of technologies, reuse and resulting properties. Prog. Mater. Sci. 72, 61–99. https://doi.org/10.1016/j.pmatsci.2015.01.004

Onwudili, J.A., Insura, N., Williams, P.T., 2013. Autoclave pyrolysis of carbon reinforced composite plastic waste for carbon fibre and chemicals recovery. J. Energy Inst. 86, 227–232. https://doi.org/10.1179/1743967113Z.00000000066

Orenda Energy Solutions, 2014. German companies use old wind turbine blades for cement [WWW Document]. Orenda Energy Solut. website. URL http://orendaenergy.com/german-companies-use-old-wind-turbine-blades-for-cement/ (accessed 5.1.16).

Palmer, J., 2009. Mechanical recycling of automotive composites for use as reinforcement in thermoset composites. University of Exeter.

Pickering, S.J., 2006. Recycling technologies for thermoset composite materials—current status. Compos. Part A Appl. Sci. Manuf. 37, 1206–1215. https://doi.org/10.1016/j.compositesa.2005.05.030

Pickering, S.J., Kelly, R.M., Kennerley, J.R., Rudd, C.D., Fenwick, N.J., 2000. A fluidised-bed process for the recovery of glass fibres from scrap thermoset composites. Compos. Sci. Technol. 60, 509–523.

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. CAMX 2015, Dallas, Texas.

RenoSam&Ramboll, 2006. Waste-to-energy in Denmark, Energy.

Rouholamin, D., Shyng, Y.T., Savage, L., Ghita, O., 2014. A Comparative Study Into Mechanical Performance of Glass Fibres Recovered Through Mechanical Grinding and High Voltage Pulse Power Fragmentation. 16th Eur. Conf. Compos. Mater. 22–26.

Sayer, F., Bürkner, F., Blunk, M., Van Wingerde, A.M., Busmann, H., 2009. Influence of Loads and Environmental Conditions on Material Properties over the Service Life of Rotor Blades. DEWI Mag. 24–31.

Schmidt, A., 2006. Life cycle assessment of electricity produced from onshore sited wind power plants based on Vestas V82-1.65 MW turbines.

Shibata, K., Nakagawa, M., 2014. Hitachi Chemical Technical Report: CFRP Recycling Technology Using Depolymerization under Ordinary Pressure.

Shuaib, N.A., Mativenga, P.T., Howarth, J., Pestalozzi, F., Woidasky, J., 2016. High voltage fragmentation and mechanical recycling of glass fibre thermoset composite. CIRP Ann. - Manuf. Technol. 65, 45–48. https://doi.org/10.1016/j.cirp.2016.04.107

Shyng, Y.T., Ghita, O., 2013. Fragmentation analysis of glass fibres recovered from hydrolysis processes, in: The 19Th International Conference on Composite Materials. Montreal, Canada.

Suzuki, T., Takahashi, J., 2005. Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger cars. Japan Int. SAMPE Symp. JISSE-9 14–19.

U.S. Energy Information Administration (EIA), 2017. How much coal, natural gas, or petroleum is used to generate a kilowatthour of electricity? - FAQ - U.S. Energy Information Administration (EIA) [WWW Document]. EIA website. URL https://www.eia.gov/tools/faqs/faq.php?id=667&t=2 (accessed 4.1.17).

Weh, A., 2012a. Final Report Summary – SELFRAG CFRP (High Voltage Pulse Fragmentation Technology to Recycle Fibre-Reinforced Composites). SELFRAG AG.

Weh, A., 2012b. Final Report Summary – SELFRAG CFRP (High Voltage Pulse Fragmentation Technology to Recycle Fibre-Reinforced Composites) – figures. SELFRAG AG.

Wingerde, A. Van, Nijssen, R., 2003. Introduction to the OPTIMAT BLADES project, in: Proc. 2003 European Wind Energy Conference and Exhibition.

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. https://doi.org/10.1016/j.compositesa.2013.02.009

World Bank, 1999. Technical Guidance Report: Municipal Solid Waste Incineration. Washington, D.C.

Yip, H.L.H., Pickering, S.J., Rudd, C.D., 2002. Characterisation of carbon fibres recycled from scrap composites using fluidised bed process. Plast. Rubber Compos. 31, 278–282. https://doi.org/10.1179/146580102225003047

Zhang, Z., 2016. Technical director of O&M service provider-Kahn Wind, Personal Communication. KahnWind.

Wind Turbine Blade End-of-life Options: An Eco-audit Comparison
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Highlights

- Lifetime environmental impact assessed for 3 types of composite wind turbine blades
- Optimal end-of-life treatments identified for currently available technologies
- Recommendations provided for future end-of-life process developments