Supporting information for

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

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1 Methodology

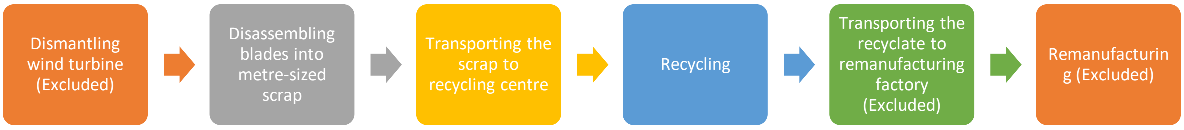


Figure S 1: Stages in a complete WT blade EoL process.

1.1 Material value

Table S 1: Referenced virgin material cost.

Material	Cost $/kg	Cost $/kg in reference year 2019	Source
vGF short	1.30	1.45	(Fiber, 2015)
vGF E-glass	1.34	1.34	(Peng, 2019)
vGF H-glass	1.64	1.64	(Peng, 2019)
GF filler	0.31	0.35	(Li et al., 2016)
vCF wind turbine (T700, large tow)	29.85	29.85	(Peng, 2019)
vCF short	23.64	23.64	Calculated
CF filler	5.09	5.67	(Oliveux et al., 2015)
Epoxy resin	5.57	6.38	(Peng, 2019)

1.2 Transportation

Offshore cases are excluded in this study due to the following reasons:

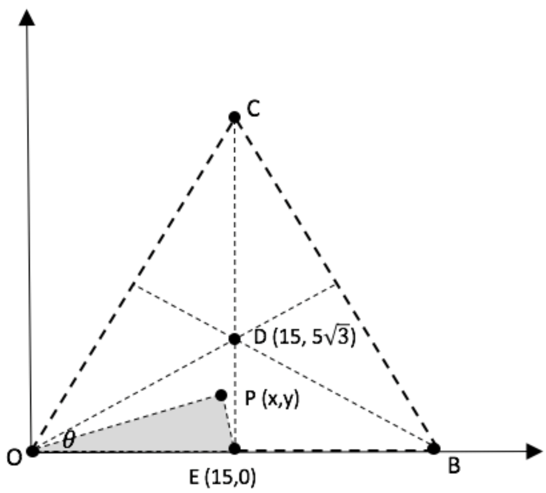
1) by the end of 2018, 96% of all installed wind energy was onshore and only 4% offshore (IRENA Statistics, 2019);

2) the designed lifetime of offshore wind turbines (between 25 and 30 years) is longer than that of those onshore (20 years);

3) large-volume installation of offshore wind energy industry has only evolved in the last 5 years (IRENA Statistics, 2019).

1.2.1 Landfill

The logistics cost of landfill depends on the distance between the wind farm and landfill site. The situation varies between regions and sites. Wind farms are located where there is an abundance of natural wind resources, hence their locations are not evenly distributed. Therefore, there is no data for the average distance between wind farms and available landfill sites and estimations must be made. Starting with Europe, the UK landfill sites map reveals that there is always an authorised landfill site within a 30-mile range (Environment Agency, 2016). Hence, we assume that the average distance between UK landfill sites is 30 miles and that they are evenly distributed. Based on these assumptions, the maximum distance between any point to the nearest landfill site is calculated as 17.32 miles and the average distance as 10.53 miles (Figure 4). These distances are based on straight line, but in reality, roads always have corners and curves. Therefore, the transportation distance must be longer. We assume the haulage distance for landfilling blade waste is 20 miles. This assumption is supported by data from the Cambridge waste management service provider, Amey Cespa Waterbeach. They confirmed that transportation is an important part of the cost of waste processing. They state, for example, that transportation distances for municipal solid waste are normally less than 20 miles, and certainly no more than 50 miles (Liu, 2016b).



- Assume the area of ODE = A

  $A = OE \times \frac{ED}{2} = 15 \times \frac{\frac{15}{\sqrt{3}}}{2} = \frac{225}{2\sqrt{3}}$

- The distance from a random point P to point O:

  $OP = \sqrt{x^2 + y^2}$

- Assume the landfill sites are average distributed, the *average distance* is

  $OP = \iint \sqrt{x^2 + y^2} \cdot \frac{1}{A} \cdot dy\, dx$

  $= \frac{1}{A} \iint \sqrt{x^2 + y^2} \cdot dy\, dx$

  $= \frac{1}{A} \int_0^{15} \int_0^{\frac{x}{\sqrt{3}}} \sqrt{x^2 + y^2} \cdot dy\, dx$

  $= \frac{1}{\frac{225}{2\sqrt{3}}} \times \left(\frac{375}{4}(4 + \ln 27)\right)$

  $= 10.53$ miles

- The *maximum distance* is OD:

  $OD = OE/\cos\theta = 17.32$ miles

Figure S 2: Average transportation distance calculation between two points based on 30 miles gap and evenly distributed assumption.

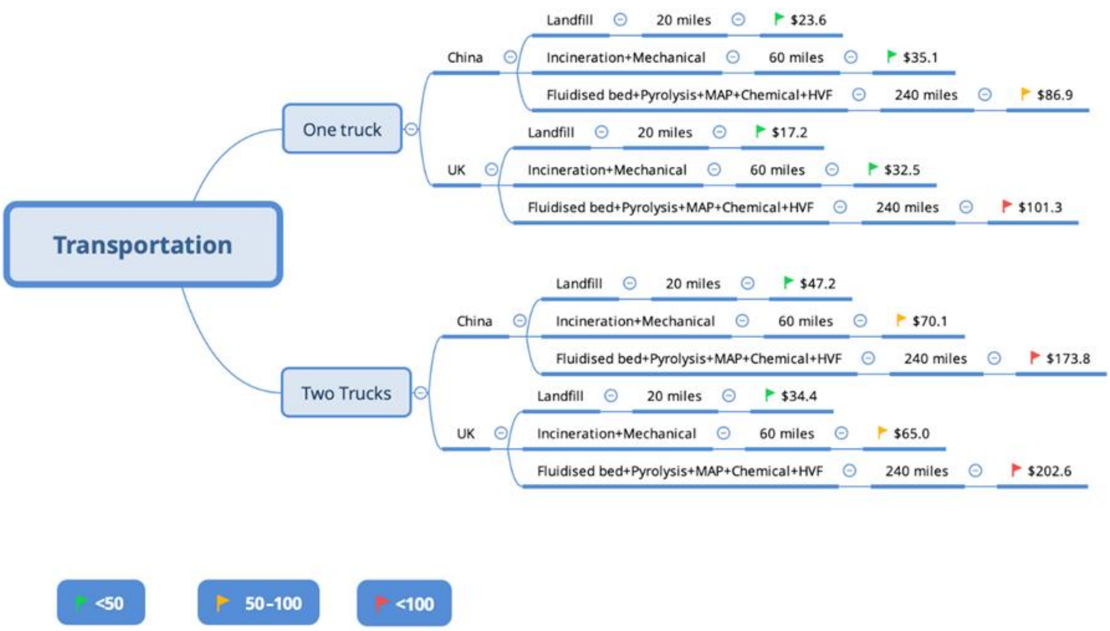


Figure S 3: Logistics cost per tonne WTB waste for different EoL options.

1.2.2 Incineration

The most up-to-date information shows that in 2013/14 there were 563 landfill sites and 61 waste incineration sites in operation in the UK (UK HM Revenue & Customs, 2016). There is no location data for incineration sites that we could use to estimate the waste transportation distance. We therefore made the same assumption as with the landfill sites: that the incineration sites are evenly distributed and the distance between them is the same. The average distance between landfill sites is 30 miles and the ratio of incineration sites to landfill sites is 61/563. The average distance between incineration sites is $1 \div \sqrt[2]{\frac{61}{563}} \times 30 = 91.1$ miles. If we apply the same method, the maximum haulage distance is 52.0 miles and we here assume an incineration transportation distance of 60 miles.

1.2.3 Mechanical, Fluidised-Bed process and Pyrolysis

Currently, no established mechanical recycling industry for composite exists. Mechanical recycling has fundamentally been an in-house operation of composite manufacturers (Job, 2014a). Hence there is no data that can be used to directly calculate the waste transportation distance. The pre-process of mechanical recycling is similar to that of incineration during which the waste undergoes several cuttings, shredding and grinding operations to be reduced to scrap which is tens of millimetre in size. The difference is that in mechanical recycling, the scrap is sent for final grinding and is separated by size while in incineration, the mm grade scrap is burnt for energy recovery. Since the complexity of both processes is similar, we assume the number of mechanical recycling sites is similar to that of incineration sites. Consequently, the waste haulage distance is the same as for incineration and mechanical recycling, at 60 miles.

Currently, the UK, Germany, Italy and the US possess one commercialized pyrolysis recycling plant each for carbon fibre composite waste recycling. One fluidised-bed process pilot factory is in operation in the UK (Job *et al.*, 2016). However, pyrolysis and the fluidised-bed process are much more complex and expensive processes than mechanical recycling and are only suitable for composite waste, not for ordinary waste, so we assume the number of pyrolysis and fluidised-bed process recycling sites is much lower than the number of mechanical recycling sites. Therefore, the haul distance is longer, and is assumed to be four times that of mechanical recycling (i.e., 240 miles or 386 km). This haulage distance covers nearly the whole of the UK and would seem to be reasonable.

In addition, the distance and load are the other key factors affecting the transportation cost. In the UK, for a large ordinary truck, the basic rate is £50 with a mileage fee of between £2 and £2.5 per mile ($76.4 + $1.9-$2.4 per km) for a truck which can carry cargo weighing up to 27 tonnes with a volume of less than 25 m^3 (Liu, 2016b).The basic rate in China is ¥900 with a mileage fee of ¥9 per kilometres ($143.2+$1.43 per km). A typical 1.5 MW grade wind turbine blade is around 45 metres long with a root of 2 metres in diameter and a tailing edge with a maximum height of over 3 metres (Sinomatech 45.2A). The blade has a cavity structure and a weight of around 8 tonnes. It is very challenging to fit such a blade into a standard large truck after it has been dismantled because of the shape and volume. It is more plausible for two trucks to carry the waste of one blade. There is no data about how many trucks are needed to carry the waste of one blade, so both scenarios are here considered, and costs given in Table 2. The distance travelled varies between EoL options.

Table S 2: Road freight cost for the UK.

Transportation Distance/miles/km	Logistics Cost one truck/t waste	Logistics Cost two trucks/t waste
20/32	\$17.2	\$34.4
60/96	\$32.5	\$65.0
240/386	\$101.3	\$202.5

1.3 Waste EoL options

1.3.1 Landfill

Landfill costs comprise three parts: the landfill gate fee, landfill tax and logistics cost. We initially aim to investigate the landfill cost worldwide, but since only the transportation cost of the UK is known, we use the UK landfill cost as an example from which to extrapolate others. In 2020, the landfill gate fee in the UK was £24 (\$31) for non-hazardous, the standard rate landfill tax was £91.35 (\$116.45) per tonne and the lower rate for waste with less than 10% organic content was £3 per tonne (WRAP (Waste & Resources Action Programme), 2019). The organic content in blade materials is generally more than 40%, so a standard landfill tax would apply (Goverment, 2016). Generally, the landfill waste is transported less than 20 miles, maybe more but not further than 50 miles. If the distance is longer than 50 miles, the increased logistics cost will make landfill uncompetitive, and this waste would be sent to other landfill sites nearby (Liu and Barlow, 2016). In the following calculation, we use a 20-mile distance and one truck transportation. In this case, the overall landfill cost is $159.2/t for glass fibre.

As CFRP has normally higher tensile properties than GFRP (Hull and Clyne, 1996) it may lead to a higher cost in fine size reduction processes such as the shredding and grinding in mechanical recycling (Hedlund-åström, 2005). As there is no need to refine the landfill waste to very fine sizes, the extra cost generated in pre-processing is negligible compared to other costs such as the transportation and landfill tax. Hence, we assume the landfill cost of the CFRP blade material is the same as GFRP blade material which is in the range of $171-$217 per tonne.

Table S 3: Landfill cost in the UK, US, China and Rest of the world.

Region	Logistics Cost (one truck) (/t)	Combined landfill cost per tonne (without transportation)	Overall landfill cost with transportation
UK	$17.2	$142.2	$159.4
US	$17.2	$50.5	$67.7
China	$17.2	$45.2	$62.4
Rest of the world	$17.2	$40	$57.2

1.3.2 Incineration

The current UK incineration gate fee is around $118.8 (£89) per tonne in 2019 (WRAP (Waste & Resources Action Programme), 2019). For the US National Renewable Energy Laboratory (NREL) states that the average cost of waste incineration is $58 per tonne (NREL, 2012). In China, the incineration cost is around $180.6 (¥1200) per tonne (Daily, 2014). The costs shown above are the incineration cost for ordinary waste, but the cost can vary for composite waste. Halliwell estimated the charge for GFRP incineration to be £120 to £150 per tonne in 2006, equivalent to $264.7-$330.9 in 2016 (Halliwell, 2006), but little information about this estimation was provided.

In addition to conventional incineration route, another widely accepted incineration is an integrated process where composite waste can be burned in a cement kiln for energy recovery with the ash used as part of fillers for cement production (Pickering, 2006). Witik pointed out the heating value of CFRP is three times higher than that of GFRP which provides a higher energy recovery potential, but the energy output of incineration has not been stated (Witik et al., 2012). In practice, as the fibre value is high, incineration of CFRP waste is unusual. More advanced recycling technologies have been more commonly considered (Jiang et al., 2009; Liu et al., 2009; Turner et al., 2011). The overall incineration cost is about €114 ($191.1) per tonne in 2019 (Jacob, 2011). The benefit is that each tonne of composite waste can substitute for 600 kg of coal as fuel for the cement kiln (Solutions, 2014). Based on EIA's conversion rate, the value of electricity generated by 600 kg coal is $58.7/t ((EIA), 2017). We assume the cost of incinerating CFRP is the same as GFRP.

1.3.3 Mechanical Recycling

In the mechanical recycling process, after being dismantled from the wind turbine, the decommissioned WT blade is cut up by mobile saw into metre-sized pieces that can be transported by a common large truck. In the second step, the metre-sized pieces are fed into a shredder reducing their size to between 25 and 100 mm. Then the scrap is fed to a hammer mill to further reduce the size of the pieces to between 5 and 25 mm (Pickering et al., 2015). The scrap is then sent to multi-stage classifications to be classified into fibrous product and fillers.

The pre-cutting cost is $40/t. The shredding cost is reported as £35/t ($58.5/t) (Li et al., 2016). The total cost for mechanical recycling of GFRP is $126.7/t summing up cost of pre-cutting ($40), transportation ($32.5) and shredding ($54.2). Since CF has a higher strength than GF (4.8 GPa for high strength CF vs 2.0 GPa for E-glass) (Design, 2016; Hull and Clyne, 1996), CFRP waste may be more abrasive to the size reduction equipment (Hedlund-åström, 2005). Hence, we assume the cost of mechanical recycling for CF is 30% higher than that of GF. The transportation range is assumed to be the same and the transportation cost remains the same as GF. Based on these assumptions, the overall cost of mechanical recycling of CFRP is $155.0/t.

Mechanical recycling of GFRP yields 28% coarse recyclate, 42% fibre and 30% powder by weight (Palmer et al., 2009). The coarse recyclate can be reprocessed once or multiple times and transformed into fibre and powder products (Palmer et al., 2009). In this case, the products will be fibre and powder only. The end product ratio is 58.3% fibre and 41.7% powder by weight. The overall loss is assumed to be 5% giving an overall yield rate of 95%. Experiments show that tensile strength of recycled fibres is reduced to 78% of that of virgin fibre (Palmer et al., 2009). The recyclate value for GFRP is thus calculated as 410.6/t.

Mechanical recycling damages the recycled CF and the resin residue on the fibre surface would significantly reduce the bonding strength between the fibre and the new resin matrix in remanufacturing (Lauzé, 2014). This leads to the recycled CF being used only as filler material, or as an additional reinforcement in plastics (Emmerich and Kuppinger, 2014; Ogi et al., 2007). Such low value applications are obviously unfavourable for high value CF (Pickering et al., 2016).

There is limited publicly available data for mechanical recycling of CFRP waste and two assumptions have been made for recyclate value estimation: a) all the recycling products are used as fillers; b) the yield rate of mechanical recycling of CFRP waste is assumed to be 100%. Similar to the GFRP waste, the overall processing loss rate is assumed to be 5wt% as for all CFRP waste EoL options. The recyclate value for CFRP is thus calculated as filler yield rate* filler cost *overall yield rate* fibre content by weight in the blade, which is 100%*5090*95%*60%=$2,901.3/t.

1.3.4 Fluidised Bed Process

Pickering et al estimated the direct expenses of a commercial-scale fluidised-bed recycling plant to be $908k with 6000 tonnes of annual capacity based on the 1997 USD price (Pickering et al., 2000). By applying the CEI changes of +57.2%, the total cost would be $1427k or $237.9/t. But they did not mention the cost of waste preparation. They considered the sheet moulding compound (SMC) component as the feedstock. This material is much smaller and easier to process than a wind turbine blade. Hence extra waste preparation is needed for the blade waste before recycling.

In the base case, we assume the blade is transported within a range of 240 miles (384 km) and that each truck is able to load all the waste from one blade. Based on these assumptions, the transportation cost is estimated to be $101.3/t (Figure 2). The pre-process cutting cost is assumed to be the same as that for mechanical recycling which is $40/t. Secondary size-reduction is needed but the scrap does not need to be as fine as in mechanical recycling, so the cost is less. We assume this cost is half that of shredding ($27.1/t). Taking all numbers into consideration, the overall cost of the fluidised-bed process would be $406.3/t.

The fibre yield rate for fluidised bed recycling of GFRP is 44%. The filler yield rate is reported as 7.6% (Pickering et al., 2000). Most organic material is burnt during the recycling process. The overall loss rate is assumed to be 5%. After being processed at 450°C, the recycled fibre strength reduces by 50% (Pickering et al., 2000). The overall recyclate value from the fluidised bed recycling of GFRP waste is

((44%*1300*50%) + (7.6%*310*100%))*95%*60%=$176.4/t.

The fluidised-bed processes for CF and GF are similar. The only differences are the different processing times and the temperature, which for CF are slightly higher, but they do not notably affect the recycling cost (Meng et al., 2017). We assume the recycling cost of CF is the same as GF, but the cost of size reduction is 30% higher than GF since CF is stronger. Hence, the total recycling cost of the fluidised-bed process for CF is calculated as $426.4/t.

The literature shows that the retained tensile strength of rCF reclaimed from the fluidised-bed process is 75% of vCF (Yip et al., 2002). As we assumed the recycled fibre value is proportional to its retained strength, the value of rCF from the fluidised bed process is 75% of that of virgin fibres. The yield rate of rCF is around 60% (Meng et al., 2017). No filler yield rate has been found, but as the process is similar, we assume the output of CF fillers is same as for GF in this process, which is 7.6%. The overall processing loss is 5%. Then, the fluidised-bed process recyclate value is calculated as (Fibre yield rate * virgin short fibre cost * recycled fibre strength ratio + filler yield rate * virgin filler cost) * overall yield rate * fibre content by weight in the blade, which is $6303.3/t.

1.3.5 Pyrolysis

Pyrolysis is a widely used thermal method, being established in commercial operations, e.g., ELG Carbon Fibre Ltd (Carbon Conversions, 2016; ELG Carbon Fibre Ltd, 2021). Publicly cost data is not available for this technology yet. The processing temperatures of pyrolysis and fluidised bed process technologies are similar, but the equipment needed for pyrolysis is simpler, and we therefore assume that the recycling cost of pyrolysis is 10% lower than the fluidised-bed process. This leads to the recycling cost of pyrolysis being $214.1/t. By putting the pre-process cost, the transportation cost and the recycling cost together, the overall cost of pyrolysis of GFRP is $382.5/t. Base on previous stated reason, CFRP needs 30% more cost in the pre-process than that for GFRP. Then, the total recycling cost for CFRP waste is calculated as $402.6/t.

The solid residue yield rate including fibre and filler is 70.7% by weight for composite waste under 400 °C (Cunliffe et al., 2003). The ratio of fibre and filler in the residue is not mentioned. Optimistically, we assume the solid residue contains 80% fibre and 20% filler by weight. In the other words, the fibre yield rate is 56% and the filler yield rate is 14%. The overall processing loss is set to be 5%. The strength of the recycled glass fibre is 52% compared to that of virgin fibre (Cunliffe et al., 2003). The recyclate value of pyrolysis recycling of GFRP is calculated as $240.5/t.

The process of pyrolysis is slightly simpler than that of the fluidised bed process which leads to relatively lower equipment costs (Tuner, 2015). The resultant recyclate performance is also marginally better. These two advantages lead to pyrolysis being the only recycling technology in commercial operation at this moment, mainly used for CFRP recycling (Job et al., 2016). However, no numerical reports regarding its cost have been found. Assumptions need to be made.

Similarly, the pyrolysis processes for CF and GF are quite similar but with different processing times and reaction temperatures (Barnes, 2015; Meng, 2017). As with the fluidised-bed process, we assume the recycling cost remains the same as for pyrolysis of GF and that the pre-process cost increases by 30%.

The tensile strength of rCF recovered from pyrolysis is reported as 80% to 96% of vCF (Meyer et al., 2009; Onwudili et al., 2013); we adopt a conservative value, 80%. This aligns well with the reported rCF price of 70-80% of the virgin fibre price by ELG (ELG Carbon Fibre Ltd, 2021). We assume the yield rate for CF is the same as for GF which is 56% for the fibre, and 14% for the filler. The recyclate value of pyrolysis recycling of CFRP is \$6478.9/t.

1.3.6 Microwave Assisted Pyrolysis (MAP)

The main advantage of microwave assisted pyrolysis (MAP) is that it is energy saving. In the process, the material is heated in its core, so the heat transfer is very fast and potentially saves energy (Job et al., 2016; Lester et al., 2004). The energy consumption of MAP recycling is around 10 MJ/kg which is only ¼ that of conventional pyrolysis (Suzuki and Takahashi, 2005). So far, MAP has not been successfully commercialised.

No MAP recycling cost estimation has been found and so assumptions are made as follows. As shown in Section 2.4.4, for the fluidised bed process the energy cost is around 50% of the recycling cost. Because both the fluidised-bed process and MAP are thermal recycling methods, MAP energy costs are assumed to comprise the same proportion of the final recycling cost, namely 50%. Furthermore, as the MAP recycling mechanism is similar to pyrolysis except for the heating method, MAP is assumed to have a similar cost level including equipment, labour and transport. The different heating methods lead to energy saving for MAP and also energy cost. MAP energy consumption is around ¼ that of conventional pyrolysis and we have assumed that the energy cost comprises 50% of the recycling cost, so the recycling cost of MAP is (50%*1/4+50%)*$218.7=$133.8/t. The pre-process costs and the transportation costs are same as conventional pyrolysis. Putting all these together, the overall cost of MAP is $302.2/t.

There is no literature to indicate the tensile strength and yield rate of GF recycled through the MAP process. However, the retained flexural strength of composite made with 25 wt% GF recovered through MAP from decommissioned WT blades has been reported as 83% compared to that made with 100 wt% virgin GF. The flexural modulus drops by 25% (Åkesson et al., 2012). As the mechanisms of MAP are similar to those of conventional pyrolysis, we daringly assume the tensile strength of recovered fibres and the yield rate of MAP recyclate to be the same. The recyclate value is thus taken to be same, namely $240.5/t

We assume the processing cost of CF MAP is the same as for GF MAP and that the yield rate is the same as in conventional CF pyrolysis. Only the cost of size reduction is higher. Hence the total recycling cost is calculated as $322.3/t. The rCF appears to have a better retained strength compared to the fluidised-bed process and conventional pyrolysis at 80% that of vCF (Lester et al., 2004). The recyclate value is $6478.9/t.

1.3.7 Chemical Recycling (Hydrolysis/Solvolysis)

Table S 4: Typical cost of lab equipment for thermal and chemical recycling depending on the specification and volume. Source: (Cole-Parmer, 2017; Rucklidge, 2017)

	UK	Compared to convection oven
Lab convection oven	~£1,000 or $1,300	100%
Lab vacuum oven	~£3,000 or $3,900	300%
Chemical reactor pressure vessel	~£25,000 or $ 32,200	2500%

Attempts have been made to recycle composite though hydrolysis or solvolysis under various temperatures, pressures, solvents, and under subcritical or supercritical conditions. Most of the recycling reactions work under high pressure and a high temperature which requires sophisticated chemical reactors and, furthermore, leads to high costs (Oliveux et al., 2015). Moreover, in the fluidised-bed process and pyrolysis, the waste is processed consecutively. In chemical recycling, the waste is batch processed which leads to a lower processing capacity and to a higher unit processing cost than that of thermal recycling. Many chemical recycling methods with different reactive media and conditions have been tested. Currently, all chemical recycling technologies are still at a laboratory scale, so recycling costs have not yet been estimated. Based on the complexity of the chemical recycling process and high equipment requirements, we assume the cost of chemical recycling is triple the cost of the fluidised-bed process, and is $713.6/t. Cutting and size reduction costs and transportation costs are assumed to be the same as for thermal recycling. The total cost of chemical recycling is then $882.0/t.

Chemical recycling is able to recycle not only fibre and filler, but also reclaim the high value resin (Yang et al., 2012). The tensile strength of recycled GF is between 47% and 67% of that of vGF (Shuaib and Mativenga, 2015). A median has been taken as 58% for the recyclate value calculation (Kao et al., 2012). The yield rate is nearly 100% (Keith, M. et al., 2016). All solid output is assumed to be fibrous product. The overall processing loss is set to 5%, which is mainly loss in feedstock preparation. The recycled fibre value is 58%*1300*100%*60% (fibre ratio by weight) *95% = $429.8/t. The recovered resin is degraded as well (Dang et al., 2005; Yang et al., 2012), but the actual performance and yield rate of the reclaimed resin have not been stated in the literature. The resin performance is assumed to be 50% that of new resin. The reclaimed resin value is calculated as 50%*5571*40% (resin ratio by weight) *95% = $1058.5/t. The total recyclate value from chemical recycling of GF is therefore $1488.3/t.

For CF chemical recycling, the recycling cost and transportation cost have been assumed to be the same as for GF. The pre-process is 30% higher than for GF recycling making the total recycling cost $902.1/t.

The retained tensile strength of rCF recovered by chemical recycling is reported as 87% to 106% of vCF with various reactive media and conditions (Bai et al., 2010; Hyde et al., 2006; Jiang et al., 2009; Liu et al., 2004; Liu et al., 2009; Okajima et al., 2009; Okajima et al., 2012; Piñero-Hernanz et al., 2008). We here take a median value of 96% for the recyclate value calculation. The retention rate of fibre after the solvolysis process has been claimed to be nearly 100% (Keith, M.J. et al., 2016). Moreover, the yield rate (100%) and retained value (50%) for resin are assumed to the same as in the assumptions made in GF chemical recycling. The overall process loss rate is set to be 5% including the loss in the pre- and post-processes. The recycled fibre value as $12933.8/t and the recycled resin value is $1,058.5/t. The total recyclate value is $13992.3/t.

Due to the low value of GF and the significant performance loss, for each tonne of waste recycled, the value of the recycled GF, $430, is much lower than the recycled resin value $1,059 and the recovered resin plays a dominant role in the GF recyclate. In contrast, in CF waste recycling, the value of the recovered resin, $1,059, is quite low compared to the substantial value of the rCF, $12933. From an economic perspective, the most important recyclate transits from resin to fibre as we move from GF to CF. Because of this, the recycling process settings should be optimised for recycled fibre performance and fibre yield rate rather than resin.

1.3.8 High Voltage Fragmentation (HVF)

High voltage fragmentation (HVF) uses repetitive high voltage electrical pulse discharges within a dielectric liquid environment (typically water) to disintegrate solid material. The voltage required is normally between 100 - 200 kV (Shuaib and Mativenga, 2016). Such a reaction has very high requirements in terms of equipment, so the recycling cost is assumed to be higher than that of conventional thermal recycling. However, since HVF does not need a high pressure chemical reactor and the reaction medium is water which is cheaper than strong acid solvent, we assume HVF costs are slightly lower than those of complex chemical recycling. We assume the recycling cost of HVF to be 2.5 times that of the fluidised-bed process which is $594.7. Adding on the cutting and transportation costs, the total cost of the HVF process is $763.1/t.

The tensile strength of HVF reclaimed GF is reported as 88% that of virgin glass fibre (Rouholamin et al., 2014). No yield rate data has been reported in the literature. The yield rate is assumed to be 90% in the base case. The overall processing loss rate is set to be 5%. We assume all outputs from this process are fibrous products, making the HVF recyclate value $586.9/t.

No literature focusing on the CF HVF processing cost has been found. We assume the recycling cost of HVF for CF is the same as in GF which is at $594.7/t. The total recycling cost of CF HVF recycling is $783.2/t. Weh (2012) reports that the strength of a rotorcraft door hinge made with rCF from HVF is 83% compared to a virgin hinge. Due to lacking direct tensile strength, we assume the tensile strength of rCF from the HVF process is 83% of vCF. The yield rate is assumed to be the same as GF HVF at 90%. The overall process loss rate is 5%. The recyclate value is then calculated as $10,064.1/t.

1.3.9 Life extension 5 years

Since the relationship between the length of extended lifetime and cost is linear, we choose a life extension (LE) of 5 years as the base case while evaluating the sensitivity for 2 years and 10.

Two actual medium-size wind farms have been adopted to analyse the life extension cost. Both of them are 50 MW, with 10 years of operation up until 2016 and adjacent to each other in Zhangbei, 300 km North West of Beijing. Each of them is equipped with 66 units of 750 kW turbines. No detailed statistical data on the material consumption is available but estimated defect rates and material consumption data were collected from on-site visits (Table 4). The blade reparation works are classified into major, intermediate and minor works depending on the size of defects/flaws. Minor defects may exist on each blade which are mainly caused by sand/small stones hitting the blades. Intermediate and major defects caused by design defects or aging rarely happen, but they need much more material to repair and the work is more time consuming. Based on the defect rate and the material consumption for each repair, the total material usage in 2015 for these two wind farms is calculated as (100*1/200+10*1/10+0.5*2.5)*66*2*3=1089 kg. This number is in agreement with the record of maintenance team (approximate 1 tonne) (Zhang, 2016). For each wind farm, the material usage is 544.5 kg.

Table S 5: Blade defects and reparations frequency for a 10 years old wind farm near Beijing (Zhang, 2016).

Repair Size	Defect rate per blade per year	Material consumption/kg	Flaw/crack size
Major	1/200	100	1m<
Intermediate	1/10	10	20cm-50cm
Minor	2.5	0.5	10cm-20cm

As shown in Table 4, by summing up the material cost, transportation cost and labour cost, the annual total cost for life extension is calculated as $68,957 for a 50 MW wind farm. Total costs for 2-, 5- and 10-years' life extension are thus $138k, $345k and $690k, respectively. Each 750 kW turbine blade weighs 2.9 tonnes (Zhang, 2016). A 50 MW wind farm has 66 turbines. Each turbine consists of 3 blades, therefore there are 398 blades in total. Total blade weight is 574.2t. Therefore, the average cost for 5 years' life extension is $60/t.

Blade size is a key factor affecting the cost of the LE options. Because all EoL costs have been converted into the unit waste cost, i.e. USD per tonne, the weight of the blade strongly affects the unit cost. Consider the fact that the reference 750 kW turbines were the mainstream model in China between 2005 and 2006 whereas the newly installed turbines are generally 2 MW or larger (Liu and Barlow, 2017), with a corresponding increase in blade weight from 2.9 tonnes to 12-15 tonnes. If the maintenance and repair demand (repair frequency) of large blades remains the same as for small blades, material usage will increase and the reparation work will be more time consuming, but the inspection and maintenance workloads should not change significantly since this mainly depends on the number of blades. It is likely, therefore, that labour and transportation may not increase proportionally to weight and hence we assume that while material cost increases in proportion to blade size (a 4.31-fold increase in this case), the labour and transportation costs increase by a fixed 20% for large blade. After this calculation, the life extension cost of a large blade reduces to $191/t, which is 69% lower than that of a small blade. The equivalent unit recyclate value is the same as 750 kW LE 5 years which is $803/t. In this case, the net profit for LE is more than $600/t which is triple what was estimated for the base case (750 kW blade). Hence for the cost estimation on LE, blade size should be borne in mind. Data details are provided in Table S3.

An advantage of the LE option is that it postpones material consumption from new replacement blades. The financial value of this option is estimated in the same way as in the environmental impact model, namely that when designed lifetime is 20 years and the blade life is extended by 5 years, the benefits from this life extension is 25%. In the other word, an LE of 5 years saves 25% of the blade material. Since there is no price list for all the materials in blade manufacturing, an approximation needs to be made. From the bill of material for a typical 1.5 MW blade, fibre and resin constitute more than 93% by weight and the remaining materials are at low prices. Hence, we estimate the full blade material value using only resin and fibre prices. Assuming that the blade consists of 60% fibre and 40% resin, we have a value for LE 5 years of (60%*1642+40%*5571)*5/20 = $803.4/t.

Table S 6: Estimated 5 years life extension plan cost for 750 kW and 2 MW blades. 750 kW blade specification from Kahn Wind. 2 MW blade specification from Sinoma 56.8.

Blade model	750 kW	2 MW
Blade length/m	25.0	56.8
Blade weight/t	2.9	12.5
Material cost/$	3,794	16,353
Labour cost/$	61,385	73,662
Transport cost/$	3,778	4,534
Annual cost/$	68,957	94,548
5-year cost/$	344,784	472,741
Total blade material/t	574.2	2475
Cost per tonne/$	600	191
Recyclate value/$/t	803	803
Net profit/$/t	+203	+612

We assume that the material usage and workload in maintenance are the same for CF and GF blades, and thus that the labour cost and transportation cost are the same. Only material cost is different: since CF ($30/kg) is much more expensive than GF ($1.6/kg), the material cost is higher. Based on these assumptions, the cost of 5 year's life extension for a CF blade is $761/t. Taking into account the 25% extra value by avoiding new material consumption, the total recyclate value for 5 years life extension is calculated as $5034/t.

2 Results and discussion

2.1 Recycling cost variations

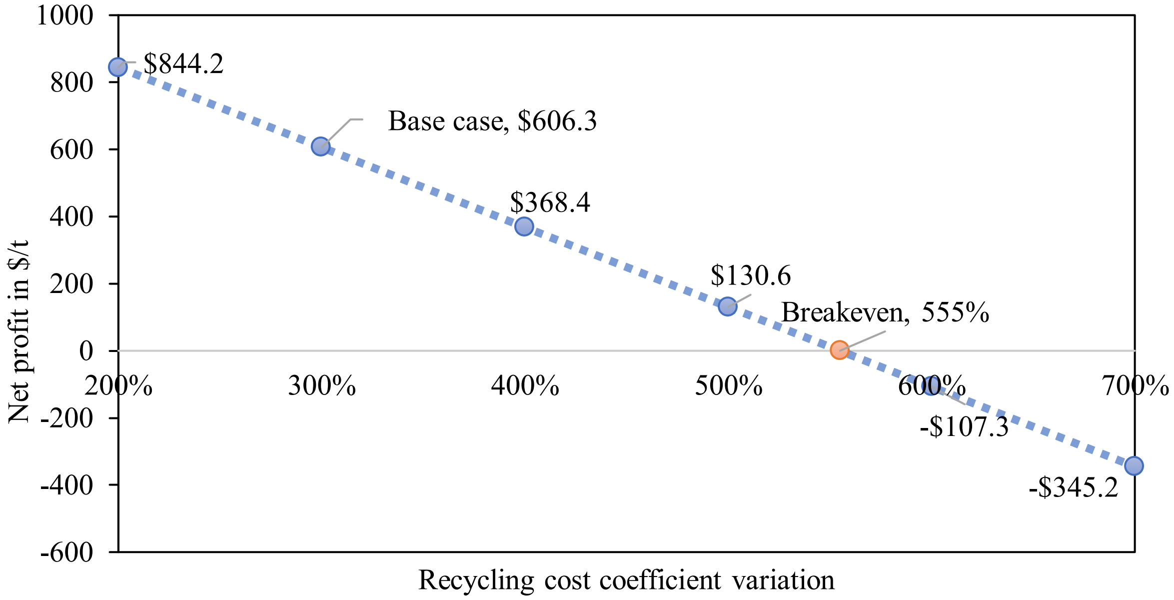


Figure S 4: Sensitivity of recycling cost for chemical recycling.

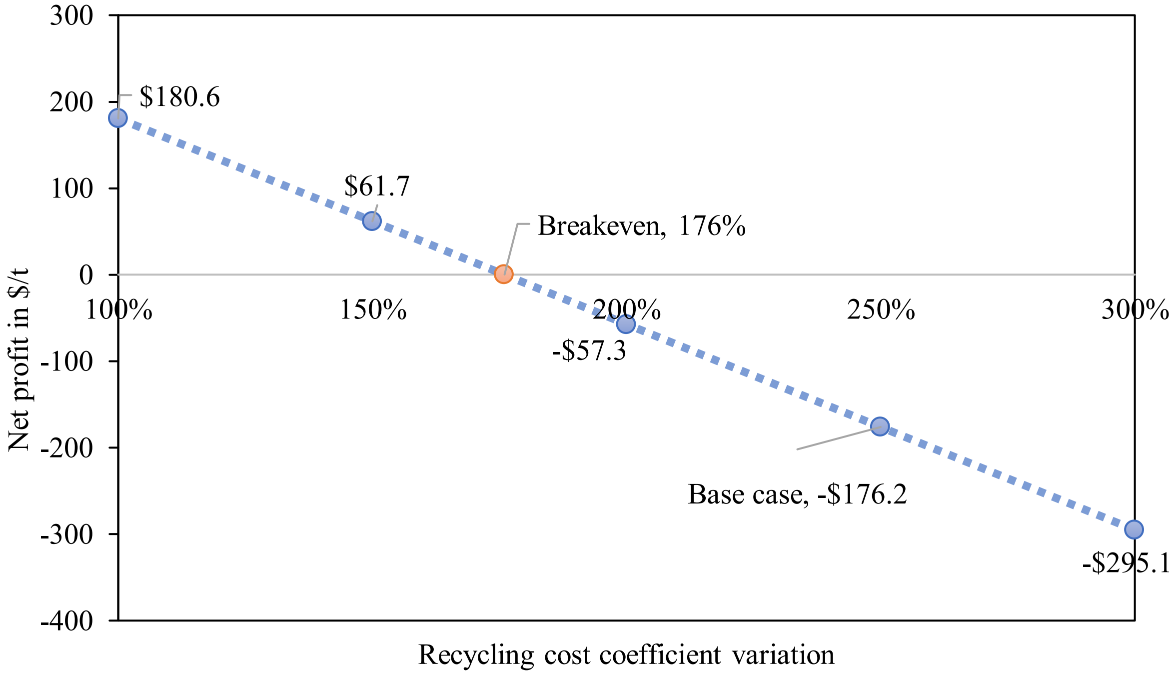


Figure S 5: Sensitivity of recycling cost for HVF.

2.2 Regional features

Table S 7: Equipment costs in the UK and China. Typical costs of lab equipment are listed but vary upon the specification and volume. Source: (Cao, 2017; Cole-Parmer, 2017; Rucklidge, 2017).

	Europe	China	Difference
Chemical reactor pressure vessel	~£25,000 or $ 32,200	~¥45,000 or $6530	~5-fold

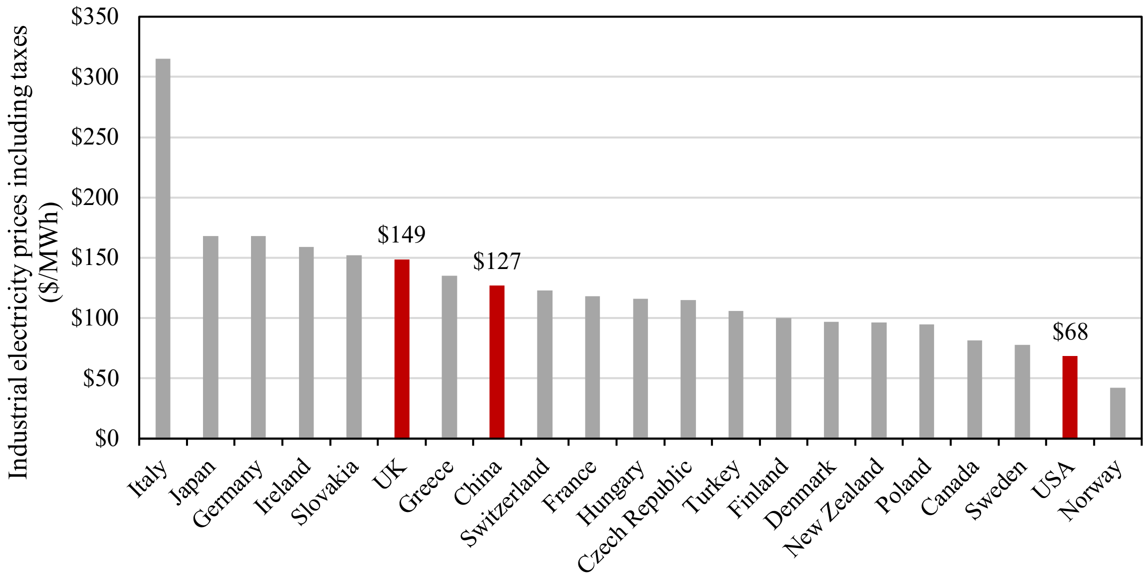


Figure S 6: Industrial electricity prices including taxes ($/MWh). Source: China National Grid and (Evans, 2015)

Table S 8: Recycling process cost index for different regions.

Cost index	Europe	United States	China
Labour cost	4	4	1
Equipment costs	5	4	1
Energy cost	1.17	0.54	1

Table S 9: Comparison of direct costs for recycling processes. Labour cost estimated based on worker daily salaries found online. Equipment cost for Europe from Pickering's data; the others calculated based on assumptions. Energy cost from Figure 10.

Recycling cost	Europe	United States	China	Ratio
Labour cost per person per day	$160	$160	$40	17%
Equipment cost per year	$299,742	$239,794	$59,948	33%
Energy cost per MWh	$148.6	$68.3	$126.8	50%

Table S 10: Comparison of net costs for GF EoL options between EU, US and China.

Net cost/$	Europe	United States	China
Fluidised bed	-229.9	-123.4	-112.7
Pyrolysis	-142.0	-41.8	-31.6
MAP	-61.7	17.5	25.5
Chemical	606.3	837.4	860.8
HVF	-176.2	23.8	44.0

2.3 Regional landfill cost variations

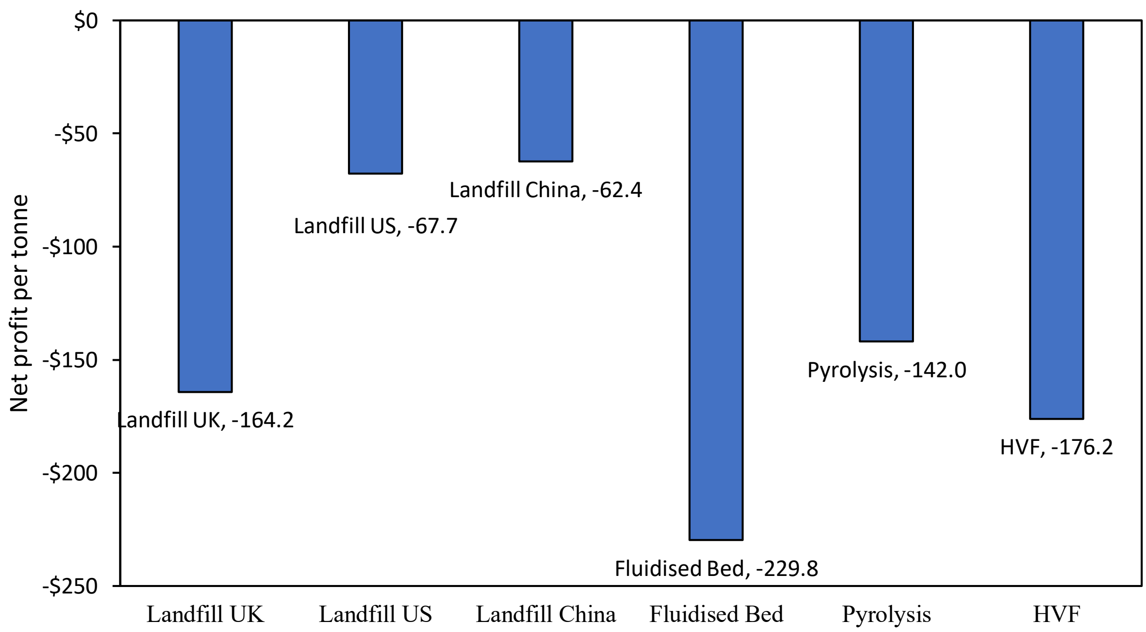


Figure S 7: Landfill costs in UK, US and China compared to the fluidised-bed process, pyrolysis and HVF (Europe process costs).

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