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Producer Responsibility: Defining the Incentive for Recycling Composite Wind Turbine Blades in Europe

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1 Abstract

Current global commitments to tackle climate change and reduce greenhouse gas emissions are resulting in increasing demand for wind energy technologies as a secure, affordable supply of energy. However, the recent expansion of wind energy generation is creating a growing waste disposal issue associated with the decommissioning of wind turbine (WT) blades in the future.

Whilst the average recyclability across the components of a modern WT has been calculated to be 80% by mass, the composite WT blades present a challenge for waste management. There is currently little legislation present for the regulation of end-of-life waste management for the wind energy industry in Europe. However, a review of European waste management policy has shown that landfill bans effectively divert waste from landfill and drive towards energy recovery.

This paper considers the producer responsibility scenarios for manufacturers to recycle WT blades. This will include an investigation into the current and future methods of WT blade disposal and specifically the potential of carbon fibre (CF) to add to the recyclability of blade systems.

Keywords

Wind energy, legislation, composite

2 Introduction

Climate change, carbon emissions reduction and security of energy supplies are worldwide issues of political concern driving environmental legislation and the development of renewable energy technologies (Hal Turton and Leonardo Barreto, 2006). Between 2007 and 2010 worldwide installed capacity of wind energy increased from 94 GW to 197 GW (WWEA World Wind Energy Association, 2011). Wind energy generation has a number of countries operating major expansion schemes both on and offshore. In 2010, China overtook the United States as the country with the most installed wind energy capacity. 16.5 Gigawatt (GW) was added over the course of the year ((GWEC) The Global Wind Energy Council, 2011), representing more than half (50.3%) of the world market. The countries with the highest total installed capacity that year were China (42.3 GW), USA (40.2 GW), Germany (27.2 GW), Spain (20.7 GW) and India (13.1 GW) (WWEA World Wind Energy Association, 2011).

The European Union (EU) climate change and energy package was adopted in 2008 with targets to reduce greenhouse gas emissions and reduce the dependence on energy sources located outside the EU (Pantelis Capros et al., 2011). The package includes three key instruments:

- **EU Emissions Trading Scheme (EU ETS).**
  The system places a cap on the amount of industrial greenhouse gases that can be emitted. Companies receive emissions trading allowances which they can trade with one another as needed. The EU climate change and energy package includes an amendment to Directive 2003/87/EC so as to improve and extend EU ETS.
- **Greenhouse Gas (GHG) Emissions target**
  Target levels for each member state were defined to meet the EU commitment to reduce greenhouse gas emissions by 20% in 2020 compared to 1990 levels.
- **Renewable Energy Sources (RES) 2020 target**
  In order to reach the target set by the EU to generate 20% of energy from renewable sources in 2020, target levels were defined per Member State.

The National Renewable Energy Action Plans (NREAP) follows from the implementation of the EU ETS directive. This sets out details on measures that would enable each member state to meet its 2020 target. National strategies include support schemes, cooperation mechanisms and barrier mitigation (Directive, 1999/31/EC).

Additionally, there are increasing economic incentives to reduce the quantity of CO_2 produced when generating electricity. For example, the Climate Change Levy (CCL) is a charge on energy usage for business and the public sector introduced in the UK in 2001 to encourage energy efficiency. When it was introduced, the levy was frozen at 0.43p/kWh on electricity, 0.15p/kWh on coal and 0.15p/kWh on gas (Adarsh Varma, 2003). It is in the interest of manufacturers to minimize the overall environmental impact of WTs in order to reduce potential future tax.

WT blades are critical components of the system since their aerodynamics, weight and structural properties are critical for energy capture (International.Electrotechnical.Commission, 2001). Blade designs have developed to optimise material properties, performance and economy. Blade lengths have steadily increased over time, from 12m or 15m common in the 1980s (Povl Brøndsted et al., 2005) to the recent launch of an 80m blade (Vestas, 2011). As the global wind industry grows in both number of turbines and size, so does the future waste stream of rotor blade material. Wind turbines are designed to withstand specific conditions, including extreme gusts which may cause high structural loads. The testing sequence is typically a static extreme load corresponding to fifty-year gust wind, followed by cyclic loading corresponding to a 20 year fatigue life (L.C.T. Overgaard, . Lund, E., , 2009). It is predicted that by 2034, 225,000 tonnes of rotor blade material will need to be recycled annually worldwide (Kari Larsen, 2009). Presently, most end-of-life WT blades are disposed of in landfill or burned in waste incineration plants (Kari Larsen, 2009). However, EU legislation discourages the disposal of waste to landfill and therefore methods for recycling are being investigated as an alternative.

Recycling composite WT blades is inherently difficult due to several factors:

- They have a complex material composition of fibres, matrix and fillers.
- They cannot be remoulded due to the cross-linked nature of the thermoset resins.
- During the 20 year lifetime of wind turbines, the rotor blades are exposed to various hostile conditions such as extreme temperatures, humidity, rain, hail impact, snow, ice, solar radiation, lightning and salinity (Wei Tong, 2010). As a result, the reduced quality of the fibres may not be acceptable for reuse structural components such as wind turbine blades.
- Even in the case of thermoplastics, after a 20 year life, the fibres could be damaged enough to prevent their reuse in a blade.
- The large size of the blades results in logistical problems relating to dismantling, transportation and cutting.

This research was conducted to consider the impact of producer responsibility for the wind energy industry, both from an environmental and economic perspective. Consequently, the results of this review will determine the incentives for manufacturers to implement recycling solutions for WT blades.

3 Analysis and results

3.1 Outline of the current recycling process

The average recyclability across the components of a modern WT has been calculated to be 80% (by mass), excluding the foundations (Begoña Guezuraga et al.). However, the blades, foundations and production waste of components are responsible for the majority of waste to landfill (Neil D‘Souza; Erhi Gbegbaje-Das; Dr. Peter Shonfield, 2011).

WTs primarily consist of steel, aluminium, copper, glass fibre (GF), polyester, carbon fibre (CF) and epoxy. Unlike glass and carbon fibre, metals are highly recyclable and widely recycled due to their intrinsic properties and their economic value (UNEP, 2011). Vestas WT blades, for example, are mainly composed of CF, GF, epoxy resin and polyurethane (PU) adhesive (Amaury Vuillaume, 2011). Therefore, recycling complex composites, such as WT blades presents a challenging problem.

Turbines installed today will reach the end of their design life after 20 years. During operation, wind turbines produce electricity from the wind; an abundant, renewable source of energy. For this reason, wind energy is considered to be a clean, environmentally conscious source of electricity. To maintain this image, the wind industry has a responsibility to reduce the environmental impact over the entire life cycle of a power plant. End of life waste arising from WT blades is an area which requires further research to find sustainable solutions.

The EU landfill directive (1999) sets targets to progressively reduce the level of biodegradable waste going to landfill and bans the landfilling of certain hazardous wastes such as liquid waste, clinical waste and used tyres. Each country has interpreted the directive to apply criteria and procedures for the acceptance of waste at landfills. Since 2005, Germany has enforced a landfill ban for untreated municipal solid waste (MSW). As a result, materials with a high organic content, such as WT blades with an organic content of 30%, are required to find alternative end-of-life routes.

Figure 1 below provides an overview of the waste volumes linked to WTG together with the end-of-life disposal routes associated with each material. The rest of this paper will focus on the issues relating to recycling composite WT blades.

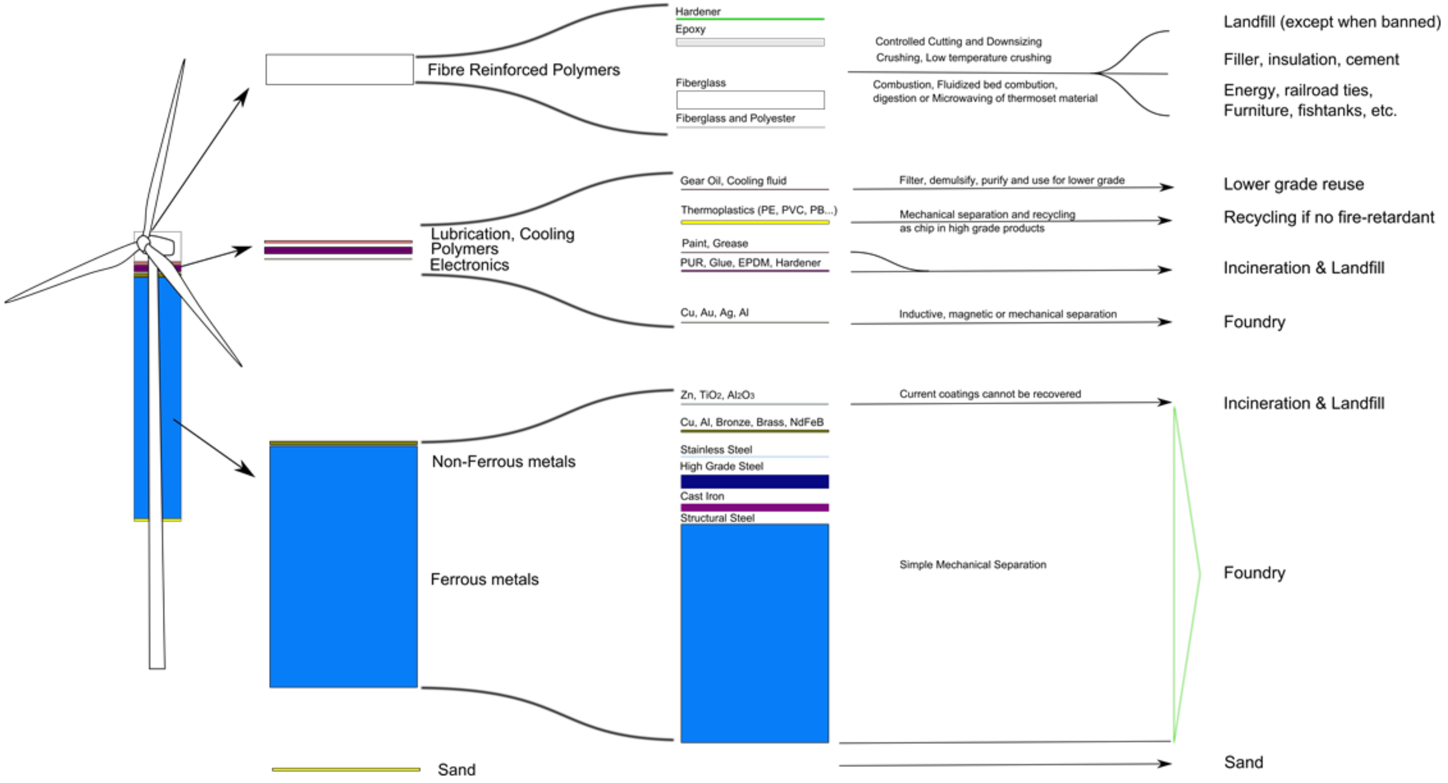

Figure 1 – Recycling WTs Outlook and Technologies.

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3.2 Technological challenges

3.2.1 Methods for composite recycling

Recycling of composites is challenging. Table 1 provides and introduction to the current methods available for composite recycling.

Table 1 – Composite recycling methods. Information sourced from (Soraia Pimenta and Silvestre T Pinho, 2010) and (N Reynolds and M Pharaoh, 2010).

Process	**Description**
Mechanical	The composite is broken down by shredding, crushing, milling or other similar processes. The resulting material can be separated into resin and fibrous products.
Pyrolysis	The composite is heated to 450°C to 700°C in the absence of oxygen; the polymeric resin is converted into a gas or vapour while the fibres remain inert and are later recovered.
Oxidation in Fluidised bed	The fluidised bed process is the most well-known implementation. It consists of combusting the polymeric matrix in a hot and oxygen-rich air flow of 450°C to 550°C.
Chemical	The polymeric resin is decomposed into oils which free the fibres for collection.

The simplest method is mechanical recycling, however the recycling process damages individual fibres; reducing the mechanical performance. The recycled material produced is of low value and cannot be substituted for virgin material. Typically it is used for much less demanding applications (Jae R.Youn Young S. Song, Timothy G. Gutowski, 2009) such as fillers for artificial wood or asphalt in the construction industry (S.J. Pickering, 2006). European legislation (explained further in section 3.5) demands that all decision on waste disposal takes into consideration the waste hierarchy. Landfill is therefore the lowest priority and recycling and/or energy recovery should be considered as an alternative.

3.2.2 Energy recovery

Energy recovery is successfully used in countries like Germany or Denmark; composite waste is mixed with 10% MSW to practically dispose of waste (S.J. Pickering, 2005). However, incineration can only recover the calorific value of the material mainly provided by the organic fraction within fibre reinforced composites. It is therefore economical to maximise the calorific value of materials to produce high energy outputs. An analysis of the material composition can be used to estimate the calorific value of WT blades to determine the technical and economic performance of incineration. The calorific values of the main materials within a WT blade are outlined within Table 2 to consider the potential for energy recovery. As glass fibres are considered incombustible, the calorific value of a fibre reinforced composite generally depends on the proportion of polymer and CF (S.J. Pickering, 2005).

Table 2 – Energy content and average calorific value of main materials within a WT blade

	Material	Energy intensity (MJ/kg)	Average calorific value (MJ/kg)
Polymer	Polyester (PE)	72	43
	Epoxy (EP)	80	30
	Polyvinyl chloride (PVC)	80	17
Fibre	Glass fibre (GF)	32	-
	Carbon Fibre (CF)	286	34[1]

Fibre Reinforced Plastics have been effectively burned in cement kilns as the glass reinforcement and fillers commonly used in composites contain minerals that can be incorporated in cement (S.J. Pickering, 2005).

3.3 Outline of the materials market

There are several factors that can affect the suitability of recycling, but the most important business consideration is whether there is a market for the recyclate (N Reynolds and M Pharaoh, 2010). Individual companies that assume responsibility for their waste management suffer, under certain circumstances, from the economies of scale and transportation costs that exist in waste management. Therefore, it is important to ensure there is a reliable feedstock; this is often achieved by setting up collective programs. The main materials to be recovered from recycling WT blades are glass and CF; this section will investigate the market for these materials.

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[1] The calorific value of CF depends on the percentage of carbon content. The calorific values of anthracite (34 MJ/kg), 98% carbon content; charcoal (30MJ/kg), 90% carbon content and coal (15-27MJ/kg), 70% carbon content (International, E.P., 2008. Carbon Char, 03 - Data Sheet 2 - Carbon Char - Low Resolution, p. 2.) are included as a guide.

3.3.1 Glass fibre

Fibre reinforced composites are lightweight, strong and chemically inert (Jae R.Youn Young S. Song, Timothy G. Gutowski, 2009), for these reasons they are increasingly applied in a wide range of applications. The aerospace industry in particular has incorporated large amounts of composites within products. For example, the Boeing 787 Dreamliner consists of 50% composite material by weight and has been “designed to be more environmentally progressive throughout the product lifecycle”(Boeing, 2011).

In 2010, the production volume of glass Fibre Reinforced Plastics (FRPs) in Europe was a total of one million tons, an increase of 25% compared to 2009 (Elmar Witten, 2010). This increasing activity has resulted in significant research into methods for recycling fibre reinforced plastics. However, the cost of recycling operations and lack of a market for the recyclate has been identified as the main barriers towards the implementation of operations (S.J. Pickering, 2005). If future legislation requires that recycling routes are available for Glass Fibre Reinforced Plastic; the market for recycled GF needs to be developed for recycling operations to become viable.

GF composites represent 98% of the composites currently manufactured in the UK (Stella Job, 2010). However, there is little financial incentive to recycle GF composites due to the limited application and low value of the recyclate. The prospects for recycling CF composites are considered to be a more attractive owing to high value of CF and wide range of end-use applications (S.J. Pickering, 2006). When carbon fibre was first produced in the late sixties the price was £200/kg (SP.Systems, 2001). By 1996 the price had dropped to £15-40/kg (SP.Systems, 2001) and in 2009 the price of CF dropped to £13/kg (Stella Job, 2009). Glass reinforcing fibre used in polymer matric composites ranges from £1-2/kg (SP.Systems, 2001). The market for CF is discussed in the next section.

3.3.2 Carbon fibre

CF is used within turbine blades to optimize stiffness-to-weight ratios as blade lengths increase in size. CF has several advantageous properties ideally suited to a range of applications, as shown in Table 3. As the demand for CF increases, there is the need for both a reliable and sustainable source of supply, since shortages have been feared in the past (Pimenta, et al., 2010). CF is usually made from the lighter components in crude oil (Propane or Propylene). From these basic precursors a longer polymer (PAN) is catalyzed to then be spun and carbonized at very high temperature. A few factors make CF’s price volatile: its dependence on the price of fossil fuels and the heavy investments in machinery and energy required for its manufacturing (Dr. Alvaro Feito-Boirac, 2011). Despite on-going supply and pricing issues, there is a worldwide demand for CF and despite the advantages associated with CF composites, waste disposal is still an issue and several recycling projects have been developed as a result (Pimenta, et al., 2010). This offers WT manufacturers an opportunity to both increase CF content and recover a high value product. This is an area worth investigating further.

Table 3 - CF and GF properties (SP.Systems, 2001)

Material Type	**GF**	**CF**
Tensile Strength, Gigapascal (Gpa)	3.45	3.50
Tensile Modulus, Gigapascal (Gpa)	86	215
Density, gram per cubic centimetre (g/cc)	2.5	1.8
Specific Modulus	34	120

The CF composite industry is expected to see significant and continued growth as a result of new applications in aerospace, renewable energy, automotive and general industry(Stella Job, 2009). A report for the Department of Business Innovation and Skills found that the leading end use of CF composite parts produced in the UK is Aerospace (36%), followed by Wind Energy (33%), with the Automotive, Marine and Industrial sectors each with a share about the same size (8%)(Stella Job, 2009). This is shown in Figure 2.

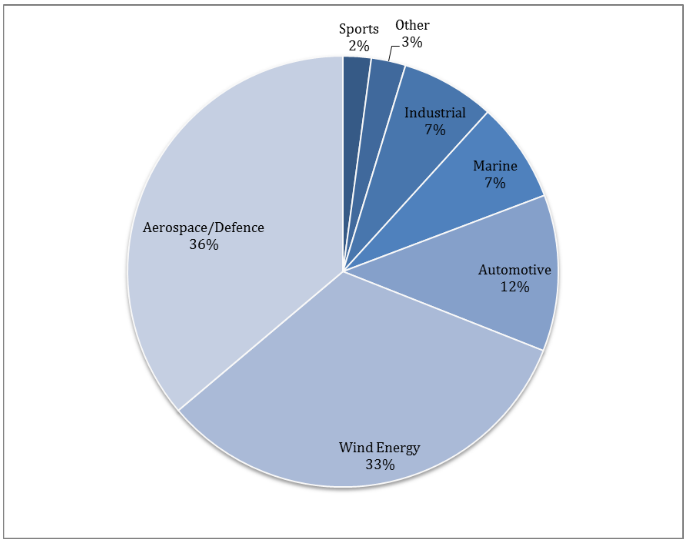


Figure 2 – UK end use of CF composites (by industry) (Stella Job, 2009)

Current commercial production of recycled CF is suitable for nonwoven, short-fibre composites used in non-structural applications such as aircraft and vehicle interiors (G Jiang and S.J Pickering, 2008). Manufacturers can also use processed recyclate as a filler or reinforcement in new products, reducing costs and environmental impacts from waste disposal. CF has several advantageous properties that can be incorporated into new products. For example, CF recyclate can be ground and mixed with a polymer to produce thermally and electrically conductive materials able to be moulded within new products. It can also improve the durability of paint, cement and other building materials (George Marsh, 2008).

Large investments are being made worldwide in CF recycling technology. In April 2011, the Carbon Faserverstärkte Kunststoffe (CFK) Valley stade Infopoint was opened. A total of €71 million will be invested in the research centre, where Dow and Invent are working to develop CF composite recycling processes for mass production (Malcolm Harold, 2011). It has been predicted that there will be increased demand for recycled CF in the future due to several factors:

1. Recycled CF offers the opportunity to bridge the gap between supply and demand for virgin CF. In 2008 the estimated worldwide demand for CFs was 35,400 tonnes, this is predicted to rise to 70,800 tonnes by 2014 (Tony Roberts, 2009).
2. It is predicted that the cost for recycled CF will be lower than virgin CF. However, the market was severely hit by the financial crisis in 2009 (Vinachem, 2011) resulting falling demand and the price drop of CF by 40% to £13/kg (Stella Job, 2009). Recycled CF would therefore need to be produced at a price below that of virgin fibre to compete. This could change if the ‘green’ credentials of recycled CF are seen to be more valuable.
3. Producing CF is highly energy intensive. New CF requires 165kWh/kg to produce, whereas producing recycled CF requires 8.8kWh/kg (Reals, 2011).

Wind energy is one of the largest end uses of CF composite parts produced in the UK with a 33% share of the volume (Stella Job, 2009). Manufacturers may consider incorporating recycled CF into designs in the future, if the increasing demand for virgin material influences the supply and cost of the material. The material properties and processability of recycled CF require further research before it can be incorporated into current WT blade designs.

Several factors need to be considered before incorporating recycled CF in future blade manufacture. Research in the wind turbine blade industry is focussed on developing technology to achieve reductions in the cost of energy. Recycled CF will be used in manufacture if it has the potential to make overall cost reductions. In addition to material cost, recycled CF could indirectly affect the turbine cost by increasing the blade weight; this additional cost is difficult to quantify or justify. Changes to the manufacturing processes and tools will also result in additional costs, which have not been taken into account in this study. Blade weight is one of the many parameters that can influence the cost at which recycled CF will be able to compete with virgin CF. Initial research co-funded by the Technology Strategy Board (TSB) has found that recycled CF will become financially attractive once the price of aligned recycled CF is below 50% that of virgin fibre (Amaury Vuillaume, 2011). It should be noted that this figure heavily depends on the degree of alignment and compressibility of the recycled material product. Achievable fibre volume fractions (vf) should increase as the technology for recycling carbon fibre develops, which in turn would make recycled CF financially attractive.

The potential savings depend directly on the price of virgin fibre and of recycled CF, as shown in Figure 3. As the cost of carbon fibre increases due to increased demand, it will become increasingly financially attractive to recover the material for reuse (Brian Knott, 2011).

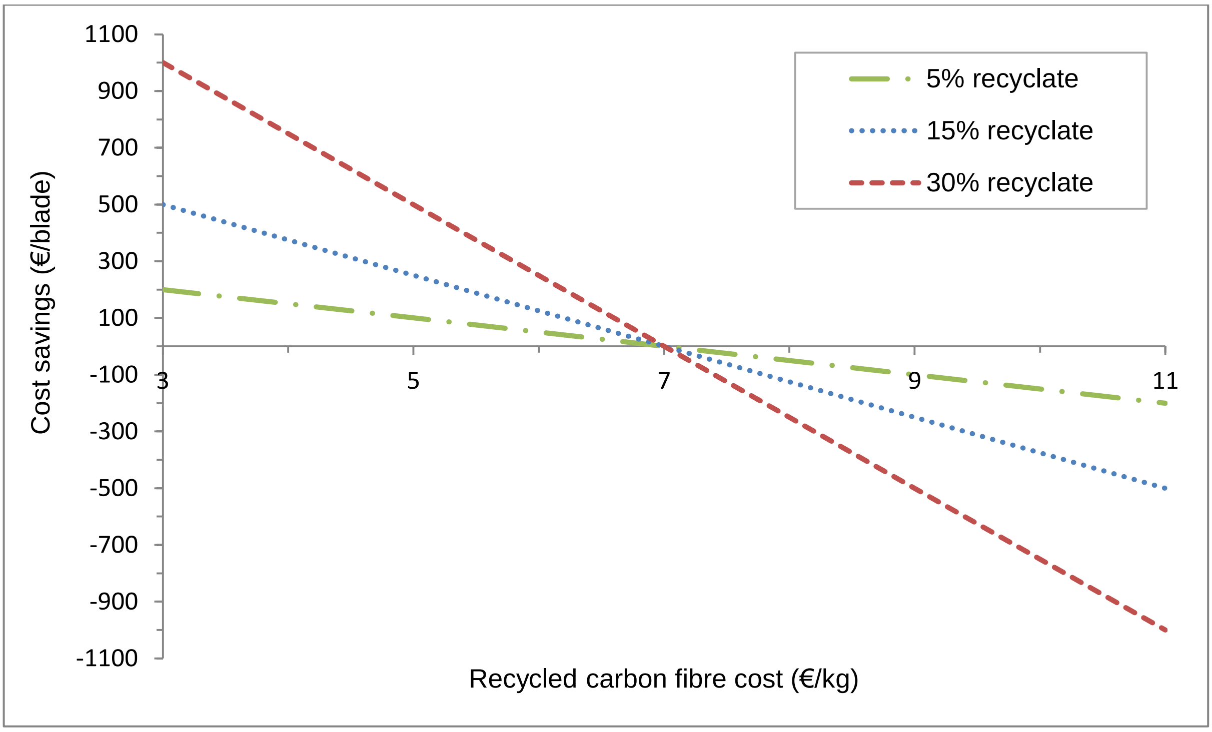


Figure 3 – Potential business case for replacing a percentage of virgin CF with recycled CF in wind turbine blades

3.4 Recycling economics

A comparative analysis was completed to determine the economic viability of recycling WT blades. Before the installation of any WT project, a decommissioning programme is designed to set out potential costs and timing for disassembling and disposing of the turbine and any associated infrastructure after end use.

Evaluating the future decommissioning costs is difficult due to several factors:

- Salvage value of material - The market value for materials is subject to unpredictable fluctuations.
- Recycling costs - As recycling methods develop, the cost of the technology is likely to decrease. The extent at which this occurs is uncertain.

- Disposal costs - This includes a tax on the disposal of waste. The Landfill tax (Directive, 1999/31/EC) is chargeable by weight and material type (Directive, 1999/31/EC). In the UK, the standard landfill tax is currently £56/tonne and will increase by £8 per tonne each year until 2014 (HM.Revenue&Customs, 2011).The disposal costs should also consider the disassembly costs including labour costs, equipment costs, transportation costs and any associated external costs.

The estimated decommissioning costs for a WT are outlined during the proposal of a project. The estimated cost can vary depending on the cost of equipment, transportation and the reuse/salvage value of the turbine. The cost of removing wind turbines, their towers, and other equipment varies considerably and is dependent on several factors including; the salvage value of steel, local transportation costs and labour rates. Table 4 outlines the estimated cost from three example projects for wind turbine dismantling and disposal. General Electric (GE) Energy (1.5 MW) and Vestas V82 (1.65MW) were considered representative of the current generation of wind turbines[1]. Recycling the blades would constitute 6% of the total cost for disposal of a WT and 0.14% the cost of a new WT[2].

Table 4 –Wind turbine disposal costs

	Vestas V82, 1.65MW (Alice Milanese, 2009)	Vestas V82/GE 1.5MW (Horizon.Wind.Energy, 2007)	GE Energy 1.5MW (Noble.Energy, 2007)
Removal	-£85,921	-£32,249	-£34,106
Salvage value of steel tower	£31,504	£21,317	£26,189

Turbine blade recycling[3]	-£3,500	-£3,500	-£3,500
Total	**-£57,917**	**-£14,432**	**-£11,418**

[1] GE Energy and Vestas represented 60 percent of the wind turbines installed between 2005 and 2010 in the United States, 54 percent of the installed capacity were between 1MW and 1.75MW in size (Ryan. Wiser, Bolinger, Mark, 2009).

[2] Based on £2,475,000 for the cost of a new turbine, excluding transportation and installation (Milanese, 2009)

[3] Dismantling and recycling costs based on an approximate value of £175/tonne and 20 tonnes of blade material (GHK, 2006).

3.5 Legislative drivers

According to the Environmental Services Association (ESA) (2004), 95% of environmental legislation is driven from the EU. The greatest industry demand for CF composites (other than wind energy) is in aerospace, automotive and marine & industrial. End-of-life legislation affecting these industries and other key pieces of legislation (Rebecca Stewart, 2010) likely to be of most relevance to composite materials are outlined in the following paragraphs.

3.5.1 Landfill Directive (1999/31/EC)

The landfill directive was introduced in 1999 to “prevent or reduce as far as possible negative effects on the waste, by introducing stringent technical requirements for waste and landfills.”(Directive, 1999/31/EC)

The directive requires;

- Operators to demonstrate technical competence
- An adherence to higher engineering standards
- The diversion of biodegradable waste from landfill
- The ban of certain hazardous waste from landfill
- The pre-treatment of waste prior to land filling.

Waste must be segregated and assigned to one of three landfill categories (hazardous, non-hazardous and inert) to avoid contamination.

3.5.2 End of Life Vehicles (ELV) Directive (2000/53/EC)

The ELV directive provides an example of a success framework for other industries to follow. Auto Shredder Residue (ASR) is a combination of materials such as plastics, textiles and glass, similar to the composites used in wind turbine blades. Traditionally, this material has been sent to landfill, but since the introduction of the ELV it is increasingly recycled to separate useable fractions (GHK, 2006).

The ELV directive sets rising reuse, recycling and recovery targets to reduce the amount of waste from vehicles when they are disposed. The regulation requires vehicle manufacturers to take back vehicles at the end of their life via authorised treatment facilities (ATF). The cost of treatment should be the responsibility of the producers rather than the last owner (Rebecca Stewart, 2010). The original UK regulations (Directive, 2000/53/EC-a) set out national targets for recycling and reuse as follows:

- No later than 1 January 2006 (85% recovery with a minimum of 80% recycling)
- No later than 1 January 2015 (95% recovery with a minimum of 85% recycling).

3.5.3 Incineration of Waste Directive (2000/76/EC)

The waste incineration directive aims to limit the risks that waste incineration poses to the environment and human health (Directive, 2000/76/EC). The regulations introduced strict operating condition and set minimum technical requirements for incinerators and co-incinerators of waste.

3.5.4 Waste Electrical and Electronic Equipment (WEEE) (2002/96/EC)

The WEEE Directive aims to reduce the amount of electrical and electronic equipment being produced and encourage reuse, recycling and recovery (Directive, 2000/53/EC-b). The directive places producers and distributers responsible for the associated costs of collection, treatment, recycling and recovery. The directive also aims to improve the environmental performance of businesses; producers must join an approved producer scheme (PCS) and distributers must offer a take-back scheme. Due to problems with its implementation, this directive is being recast. In January 2012, the European Parliament approved an updated version of their Directive on collection targets for WEEE that now includes photovoltaic (PV) modules. Whilst large electrical installations such as wind turbines are currently exempt from the WEEE, “the scope will be extended to cover all Electrical and Electronic Equipment (EEE) after a transitional period of six years”(Directive, 2008/0241(COD)).

3.5.5 Waste Framework Directive (2008/98/EC)

After a review in 2005, a new waste framework directive was adopted simplifying the existing waste directive and incorporating the directive on hazardous waste (91/689 EEC) and waste oils (75/439 EEC). The new directive provides a framework for collection, transport, recovery and disposal of waste; promoting waste as a secondary resource to reduce landfill volumes across Europe.

The key issues in the UK directive are (Directive, 75/442/EEC):

- Waste hierarchy - All decisions on waste policy, infrastructure and management will be expected to take the waste hierarchy into account. The new hierarchy outlined is: prevention, preparing for reuse, recycling, other recovery and disposal.
- Recycling targets – The directive sets a range of targets for increasing recycling rates for household and construction and demolition (C&D) waste.
- End of waste – The directive outlines plans to develop end-of-life criteria for certain materials. Waste material that is able to compete on a level playing field with virgin material would be free from regulation.

The document also introduces new producer responsibility measures to increase levels of recycling, reuse and waste prevention. Member states are granted power to encourage producers of waste to sort waste into different fractions for recycling and energy recovery.

4 Motivators

The incentives for recycling WT blades will be defined by the four motivators below.

4.1 Environmental impact

“The generation and distribution of electricity has environmental impacts and effects, regardless of which energy source is used” (M Patricia Henton, 2002). Life cycle assessments (LCA) are used as a basis for assessment of environmental improvement throughout the life cycle of a power plant. Impact assessments often include the following environmental impact categories: global warming potential (GWP), acidification, human toxicity, eutrophication, wastes, and resources. Henton found that the largest impacts are associated with the raw material production, manufacturing phase and end- of-life processes of the life cycle (Charlotte Eyre, 2010).

To improve the environmental impacts of wind turbine blades, manufacturers should return to the design phase to improve the recyclability of materials at end-of-life. Thermoplastic reinforcement, metallic and/or hybrid materials could provide options to improve the sustainability of designs. Manufacturers should also consider designs that can be easily dismantled, allowing materials to separated and recycled (N C Mcdonald and J M Pearce, 2010).

4.2 Legislation

Producer responsibility policy legislation for the wind industry is highly likely to appear in the EU first. According to the Environmental Services Association (ESA), as indicated in the previous section, the EU has driven 95% of environmental legislation over the past 10 years. European legislation is focussed on sustainability, avoiding the generation of waste and enhancing efficient use of natural resources by applying the concept of life-cycle thinking. Furthermore, current legislation promotes reuse and recycling to enable a recycling economy.

The UK government is giving consideration to restrict the landfilling of biodegradable and recyclable wastes, including landfill bans (Defra, 2010). Given the trends apparent in current legislation, it can therefore be assumed that future legislation will evolve along similar lines of life-cycle thinking.

The introduction of current waste legislation in the automotive industry (ELV) has brought forward important lessons that can be utilised in industries that share similar issues of disposal for composite materials. If legislation is introduced within the wind energy industry it is likely to be similar to ELV legislation which encompasses Extended Producer Responsibility (EPR) by introducing set recycling and recovery targets for manufacturers. Developing strategies for sustainable disposal of WT blades at an early stage will enable ecological and sustainable systems to be available in time. WT manufacturers should take the initiative and not wait to be forced by the legislator. Investigating solutions now will provide time to develop efficient systems and drive down technology costs; therefore reducing the economic penalties from legislation.

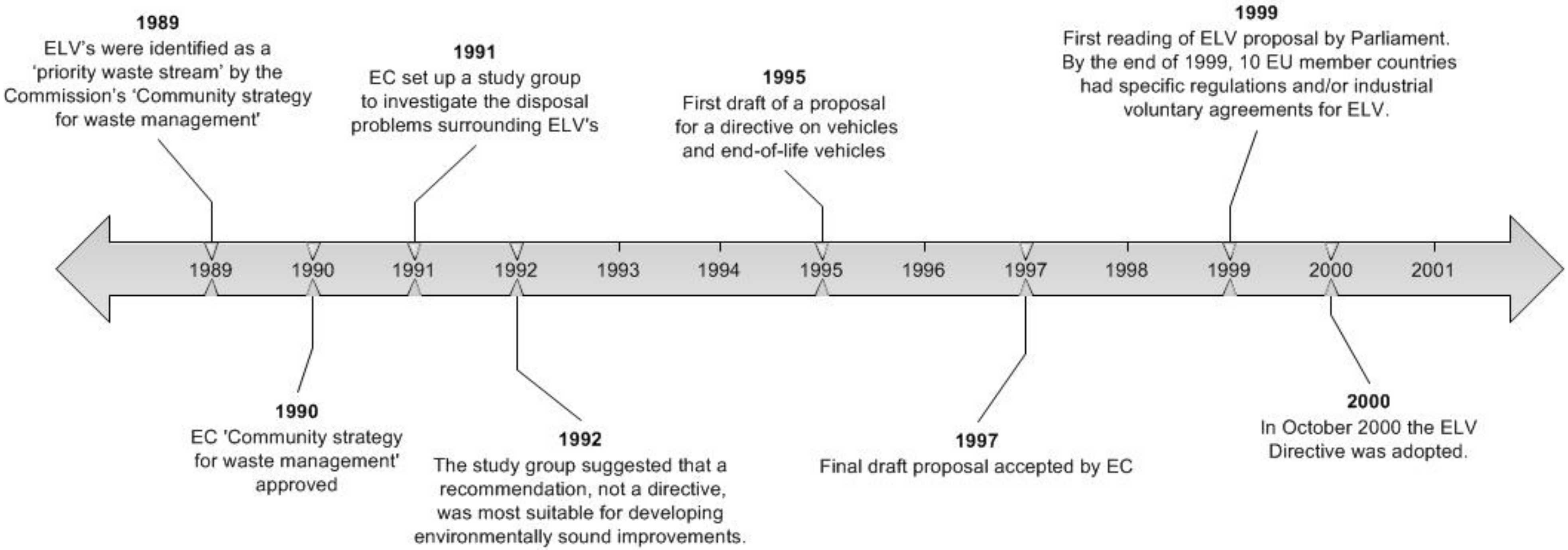
4.3 Economic opportunity

The externalities of wind energy estimate the hidden benefits/damages of electricity production. Externalities are broadly defined as the “benefits and costs which arise when the social or economic activities of one group of people have an impact on another, and when the first group fails to fully account for their impacts” (European.Commission, 1994). Externalities can be classified into two main categories; environmental and non-environmental. Environmental externalities consider areas such as: human health, occupational health, ecological impacts and climate change. Whereas non-environmental externalities consider subsides, research and development costs, employment and effects on Gross Domestic Product (GDP). External costs are often difficult to quantify, however a study by the European Wind Energy Association (EWEA) estimates the external costs associated with wind energy range from 0.05 to 0.25 c€/kWh (Eurocent/Kilowatt hour). Therefore, the external costs associated with the UK installed capacity in 2010 could be from €5 million up to €26 million (Olav Hohmeyer et al., 2005).

Manufacturers should investigate recycling options for end-of-life composite waste as soon as possible to efficiently cope with the future implications of composite disposal whilst recovering valuable resources and avoiding the increasing cost of landfill. Lessons from the industry response to the ELV directive and the WEEE directive provide valuable feedback for composite disposal in the wind industry.

5 Discussion

Extended producer responsibility (EPR) states that the manufacturers and producers of products are responsible for any life cycle impacts produced (Larsen, 2009). This has been applied across a number of other sectors such as automotive and electronic and electrical equipment (which from January 2012 now includes photovoltaic (PV) modules) and may be extended to cover wind turbines “after a transitional period of six years” (Directive, 2008/0241(COD)). The EU regulation-making process started in 1989 when ELV was identified as a ‘priority waste stream’ (Directive, 1999/31/EC) and in 2000 the ELV Directive was adopted. Figure 4 illustrates the timeline for development of ELV legislation within the EU. If end-of-life waste legislation in other industries is implemented; a similar time frame can be expected.



1989
ELV's were identified as a 'priority waste stream' by the Commission's 'Community strategy for waste management'

1990
EC 'Community strategy for waste management' approved

1991
EC set up a study group to investigate the disposal problems surrounding ELV's

1992
The study group suggested that a recommendation, not a directive, was most suitable for developing environmentally sound improvements.

1995
First draft of a proposal for a directive on vehicles and end-of-life vehicles

1997
Final draft proposal accepted by EC

1999
First reading of ELV proposal by Parliament. By the end of 1999, 10 EU member countries had specific regulations and/or industrial voluntary agreements for ELV.

2000
In October 2000 the ELV Directive was adopted.

Figure 4 - Development of ELV legislation within the EU

EPR principles have been introduced through current waste legislation in the automotive industry (ELV) and electrical and electronic equipment (WEEE).These industries share similar issues of disposal for composite materials.

In 2010, 37, 642 MW of wind energy was added worldwide, which will result in over 225,000 tonnes of end-of-life composite waste annually worldwide by 2034 (Kari Larsen, 2009). End of life vehicles are is estimated to reach a volume of 14 million tonnes by 2015 just in Europe alone as the number and average weight of vehicles increases (GHK 2006); this can be expected to further increase beyond 2015. Compared to annual composite disposal in the entire world, composite blades remain magnitudes lower in comparison. (Kari Larsen, 2009).

The automotive shredder residue (ASR) fraction is typically around 20 – 25 % of the weight of the ELV, suggesting a worldwide annual production of 10 million tonnes (Ron Zevenhoven; Loay Saeed, 2002). The UK targets for end-of-life vehicles were staggered to allow development to occur. The 2006 targets set a minimum of 85% of vehicles must be reused or recovered (including energy recovery) and at least 80% of this must be reused or recycled. Targets for 2015 are increased to 95% and 85% respectively. To meet these targets, recycling infrastructure is developing and cost reduction in the technology for treatment and recovery of material are expected.

Several recycling technologies for treating automotive shredder residue (a complex mix of body shell materials left after vehicle dismantling) are in varying technological stages of development (GHK, 2006). These are potential disposal routes for waste blades. Carbon and glass fibre recovery systems are also reaching a mature stage. Commercial scale systems are currently in operation, and the recycled carbon fibre reinforced plastics being produced demonstrate competitive structural performances. The main challenges lie in developing a market for the recycled materials to ensure an economically sustainable recycled carbon fibre reinforced plastic industry. The CF market generally is commercially unstable at the moment and supply chains can be problematic but there does appear to be potential for development of a market for recycled CF (Soraia Pimenta and Silvestre T Pinho, 2010). If WT manufacturers can utilise a closed loop recycling system with a recycled CF supplier they would be insulated from these fluctuations as well as retaining confidence in material provenance. Optimally, recovered material from closed-loop recycling will provide a reliable resource considering the variability of cost and availability of CF. Further research is needed in the logistics involved with a WT recycling value chain.

However, there are some challenges involved in adapting the current design for recyclability. As mentioned earlier in the report, the complex nature of the blade material makes it difficult to reuse or recover components. Due to the large size of the blades, fibres are mechanically cut for handling issues; this reduces the properties of the material. As composites fatigue during their lifetime, fibres must be broken at their weakest point, limiting the size of recovered fibres. Furthermore, investigation into the safety aspects of milling glass and carbon fibre-reinforced plastics has identified several health issues; including the risk of fine dust particles causing respiratory problems (Ranga Komanduri, 1997). Researchers have been working on solutions to these challenges. Recent research investigates if WT blades can be manufactured from thermoplastic composites which would allow direct fibre recovery and resin recycling (Marsh George, 2010; S Joncas, 2010; George Marsh, 2010). However, current practices separate the resin for low value reuse and break fibres at their weakest point.

Composite materials have an organic content of more than 30% and as a result are at risk of being banned from landfill in future European policy (Jacobs, 2008). However, it is suggested that composite materials should be entitled to a separate category due to the positive environmental impacts over the lifecycle associated with incorporating composites into designs (Amaury Vuillaume, 2011). For example, weight savings could be realised by switching from metal to composite in automotive structural components, resulting in reduced weight and hence lower fuel consumption (Stewart Richard, 2010).

6 Conclusions

Since the EU is at the forefront of environmental legislation, any regulations impacting the wind industry are likely to impact on the EU first compared to anywhere else in the world. However, the EU currently places a greater priority on encouraging renewable energy and therefore there are no plans for regulating composite turbine blade disposal. In the future these priorities may change. It is clear that end-of-life options for composite WT blades is an increasing issue and landfill of waste is becoming unacceptable method of waste disposal. Manufacturers need to take the first steps to develop WT blade designs for recycling to facilitate sustainable methods of waste disposal. Closed-loop recycling would provide the most sustainable solution (in terms of resource management); capturing fibres and processing it back into the blade. Similar issues of waste disposal in the automotive (George Marsh, 2005) and aerospace industries (Marsh George, 2008) have initiated research to address the technical and economic challenges of recycling fibre-reinforced polymers. In particular, large investments are being made worldwide into the recycling of CF composite waste with at least one commercially operating process currently available (Recycled.Carbon.Fibre, 2010). However, the material properties and processability of recycled CF need further research before it can be incorporated into current WT blade designs.

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