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A Comparative Life Cycle Assessment between landfilling and Co-Processing of waste from decommissioned Irish wind turbine blades

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A B S T R A C T

Dealing with composite waste from decommissioned wind turbine blades will become a major issue in the coming years. This study aims to determine the most sustainable disposal method for Irish blade waste in the next ten years by using life cycle assessment to compare three scenarios: Co-processing in cement kilns in Germany, co-processing in Ireland, and landfill in Ireland. The results of this study establish a baseline impact scenario with which to compare future repurposing solutions, which are higher on the European Waste Hierarchy. Co-processing is not carried out in Ireland at the moment, but as blade waste increases, there is a strong likelihood of it becoming viable. Co-processing utilizes shredded blade waste to replace fuel and raw materials in the production of clinker, whereby environmental gains are made through material substitution. Comparative Life Cycle Assessment is used to determine which scenario is the least environmentally impactful, and which of the variables has the strongest impact. Co-processing in Ireland is determined to be the least impactful, due to the material substitution and the reduced transport. Material substitution is found to have a stronger impact than increased transport between Ireland and Germany. There is, however, a concern with co-processing as a preferred method to dispose of Irish blade waste in that the ease of disposal in this fashion might de-incentivize repurposing. Future research is needed to compare the costs of co-processing to other repurposing ideas, and to develop policy that requires farm owners to set aside bonds to pay for more sustainable second life options for blade waste. This will ensure that the option of co-processing in Ireland is passed over for a more sustainable Irish alternative.

1. Introduction

Dealing with composite blade waste from decommissioned wind turbines will become a major issue in the coming years. The installed base of wind generation is growing every year in many countries. A recently released report commissioned by the Irish Wind Energy Association shows that Ireland can achieve 70% renewable energy generation by 2030 by increasing wind power capacity from 5400 MW in 2018 to 10,000 MW by 2030 (Turner et al., 2018). The Irish Government issued a Climate Action Plan in June 2019 with a target of 11,700 MW installed wind energy by 2030 (DCCAE, 2019). Wind turbines have an estimated life span of 20 years (Beauson and Brøndsted, 2016; Elsam Engineering A/S, 2004; Jensen and Skelton, 2018; Marsh, 2017) and there is an estimated 12–15 tonnes of blade material per MW installed capacity (Jensen and Skelton, 2018). Therefore, based on the installed power in 2018 and the target installed power for 2030, there will be approximately 64,800 tonnes of blade waste material that Ireland must dispose of by 2038, with a further 55,200 tonnes of waste material by 2050.

The European Waste Hierarchy (Council Directive, 2008) illustrates the preferred waste management processes, based on sustainability, with the most preferred option at the top. Fig. 1 shows

Abbreviations: DALYs, Disability Adjusted Life Years; EuCIA, European Composite Industry Association; CFRP, Carbon Fibre Reinforced Polymer; GFRP, Glass Fibre Reinforced Polymer; GWP, Global Warming Potential; ILCD, The International Reference Life Cycle Data System; LCA, Life Cycle Analysis; LCC, Life Cycle Costing; LCIA, Life Cycle Impact Assessment; LCSA, Life Cycle Sustainability Analysis; s-LCA, Social Life Cycle Analysis; SRF, Solid Recoverable Fuel.

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the hierarchy in the context of wind turbine blades. Currently, three broad options exist to manage blade waste (Ierides et al., 2018). Disposal, which includes landfill or incineration without heat recovery, is lowest on the waste hierarchy. Energy recovery or recycling is higher, and includes incineration with energy recovery, or thermal, chemical or mechanical recycling of the material for use in lower value products. Co-processing in a cement kiln can be considered both energy recovery and recycling (European Composites Industry Association, 2013). Repurposing is higher still, whereby full or parts of blades are used for different applications. Note that Prevention and Reuse are at the top of the pyramid. However, these two options prevent the creation of blade waste, and therefore are outside the scope of this analysis.

Landfill and incineration are the most common disposal practices in many countries in Europe (Corinaldesi et al., 2015; Ribeiro et al., 2015). There is no law in Ireland banning the disposal of blade waste into landfill as there is in Germany (Correia et al., 2011). However, in Ireland, landfilling costs €113 per tonne, which is one of the most expensive rates in Europe (National Competitiveness Council, 2015). New laws are anticipated which will encourage disposal methods of Glass Fibre Reinforced Polymer (GFRP), the main component of wind turbine blades, that are higher on the waste hierarchy, similar to the End of Life Vehicle Directive (European Parliament, 2000) which mandates that 95% of an End of Life Vehicle should be reused or recovered.

Recycling includes pyrolysis, mechanical processing for use as filler material, and co-processing in a cement kiln. Mechanical processing uses many approaches such as shredding the material down to 40 mm and then grinding it into mortar filler powder (Farinha et al., 2019), cutting into slender shapes for use as aggregate in concrete (Yazdanbakhsh et al., 2018), or grinding for reincorporation into composites (Palmer et al., 2009). However, these options are still in development. Co-processing requires the blade to be shredded, and then incorporated with other waste before being sent to a cement kiln for use as fuel and raw material substitution (T.Hasse, Holcim/Lafarge, personal communication, 27th June 2019). According to the European Composites Industry Associate (EuCIA), pyrolysis and mechanical processing are not viable for GFRP due to the low costs of the virgin raw material, while co-processing of GFRP in a cement kiln is viable and is currently being used. The cost of co-processing is still unknown, but is estimated to be more than landfilling.

Repurposing is higher on the waste hierarchy than recycling or recovery, and research into repurposing solutions could result in management of GFRP waste that is environmentally superior. Repurposing might include using parts of the blades for roofing on temporary or inexpensive housing (Bank et al., 2019), office and home furniture (Adamcio, 2019; "Bladesign," 2019), a city furniture project completed in Rotterdam in 2012 (SuperuseStudios, 2012), and a pedestrian bridge (Speksnijder, 2018; Suhail et al., 2019).

These different solutions (disposal, recycling/recovery or repurposing) can be comprehensively compared using Life Cycle Assessment (LCA). LCA is a widely used tool which evaluates a range of environmental impacts across the life cycle of a product or process (Çankaya and Pekey, 2019; Finnveden et al., 2009; ISO, 2006a, 2006b). LCA quantifies the impacts of a product by considering all resulting effects on the natural world, including human health, ecosystem quality, climate change, and resources. This approach eliminates problem shifting from one aspect or process to another. LCA is used in assessing waste management practices (Cherubini et al., 2009; Huysveld et al., 2019), comparative environmental analysis (Çankaya and Pekey, 2019), environmental impacts of electricity generation (Han et al., 2019), and in assessment of glass and carbon fibre production and recycling (Farinha et al., 2019; Oliveux et al., 2015; Song et al., 2009). Therefore, LCA is well suited for use in the comparative analysis of disposal methods of waste GFRP, as presented in this study.

To perform a comparative analysis, a baseline LCA must be established using GFRP disposal methods which are either currently in use or could potentially be used now. Studies have shown that co-processing in a cement kiln is environmentally less detrimental than both incineration with or without heat recovery, as well as several other recycling options (Anh et al., 2018; Hall, 2016; Job et al., 2016; Oliveux et al., 2015; Schmidl and Hinrichs, 2010). EuCIA, the European Plastics Converters, and the European Recycling Service Company claim "the cement kiln route to be the most sustainable solution for waste management of glass fibre reinforced thermoset parts" (European Composites Industry Association, 2011). EuCIA considers the cement kiln option to be classified as recycling due to the E-glass component, which makes up over 50% of the blade waste, being fully recyclable into cement components. This would place the cement kiln disposal option higher on the Waste Hierarchy than incineration either with or without heat recovery.

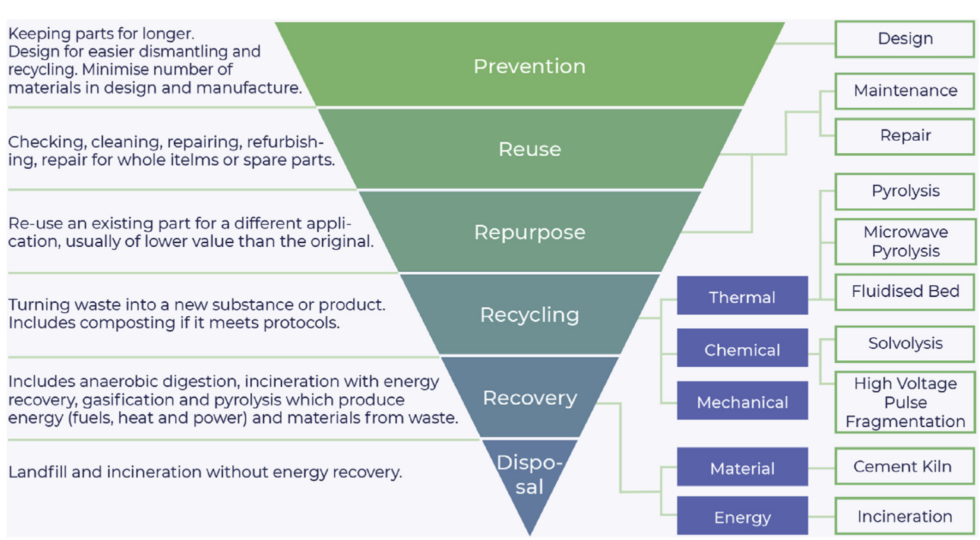

Fig. 1. European Waste Hierarchy, in the context of wind turbine blade End of Life (Ierides et al., 2018).

Co-processing of blade waste is not currently carried out in Ireland. However, there is potential for it to become a viable disposal option in the future. A cement manufacturing representative body in Ireland (B. Gilmore, personal communication, 28th May 2019) indicated that the primary barrier to co-processing of blade waste in Ireland is the cost of equipment to shred the blades. In further interviews with an Irish waste management company (Veolia, personal communication, 28th May), it was estimated that a few hundred turbines would need to be decommissioned before it would warrant a waste management company investing in the machinery to perform the blade shredding. Using the estimated 20 year blade life span, decommissioning dates were predicted using known commissioning dates (obtained from thewindpower.net). The results indicate that approximately 500 turbines are expected to be decommissioned by 2025 on the island of Ireland. This suggests that the possibility of co-processing in Ireland is strong enough to justify its inclusion as a scenario.

LCA studies of the full lifecycle of wind turbines have previously been undertaken, but most either call for landfilling of the blades (Martínez et al., 2009; Vestas Wind Systems, 2006c), suggest a recycling option that is not viable yet (Díaz Martín et al., 2016) or include an incineration process that does not exist anymore (Vestas Wind Systems, 2006a). Studies specifically on the disposal methods of wind turbine blades also exist (Cousins et al., 2019; Larsen, 2009; Liu and Barlow, 2017; Ortegon et al., 2013; Schmidl and Hinrichs, 2010), but none utilize LCA. Finally, a partial LCA exists showing emission reductions due to using blade waste in the co-processing of clinker, but the material substitution rates appear to be theoretical, and the results only include Carbon Footprint data (European Composites Industry Association, 2013). To the best of our knowledge, no LCA exists that compares actual co-processing in an existing cement kiln against landfill as end of life options for blade waste. No LCA exists comparing end of life options, including transportation impacts, for Irish blade waste.

This paper determines the best practice of disposal of Irish blade waste, and conducts the first LCA to quantify the environmental impacts of this method. It also compares the negative impact of transportation of blade waste to the beneficial gains of the use of blade waste as raw material substitution in clinker production. The research contributions in this paper are the following:

1. Comparison of the environmental impacts of the two disposal methods known to be currently in use for Irish GFRP blade waste: co-processing in a cement kiln in Germany, and landfill in Ireland.
2. Quantification and comparison of the environmental impacts of theoretical co-processing in a cement kiln in Ireland versus both co-processing in Germany and landfill in Ireland. Establishment of an environmental baseline scenario with which to compare Irish blade waste repurposing ideas.
3. Comparison of the environmental impacts of transportation distance versus raw material substitution rates in co-processing.

Quantification of the best practice for the disposal of Irish wind turbine blades will be of use to wind farm owners, decommissioning contractors, and policy makers in working to ensure this waste stream is handled in the most environmentally sound manner.

2. Methods

2.1. Goal, functional unit, and system boundaries

The goal of the LCA in this study is to compare the environmental impacts of the current and potential disposal methods for Irish wind turbine GFRP blade waste, and to establish a best case baseline disposal method. This baseline assessment can be used to determine marginal differences in impacts of future blade waste disposal options that are higher on the waste hierarchy, such as repurposing. The study is classified as Attributional LCA, as it utilizes current rather than prospective data, and reports the results as normalized environmental impacts (Ekvall, 2020).

The highest percentage of turbines due for decommissioning in Ireland are the Vestas V52 model. The V52 is rated at 850 kW and has three 25 m blades that weigh 1900 kg each (Vestas Wind Systems, 2006b). The functional unit is therefore based on the total mass of three blades in one V52 turbine residing in Ireland, and is defined as *'Disposal of 5.7 tonnes of blade waste decommissioned in Ireland'*.

The system boundary starts after the blade has been removed from the hub and cut into 1.5 m^2 pieces which are lying onsite as blade 'waste', as determined by the turbine owner/operator. Therefore, no impacts from the production or the lifetime use of the blade have been included. The choice of 1.5 m^2 pieces reflects previous decommissionings of turbines in Ireland, however the size of the pieces may be larger in some other cases. The dismantling and cutting of blades into 1.5 m^2 pieces is also not included for comparison, as this step is the same across all scenarios. All impacts due to transporting and processing of the blade up through its final disposal either into the landfill, metal recycling or as fuel and raw material for co-processing in a cement kiln are included.

The scenarios chosen are: co-processing abroad (Scenario 1); co-processing in Ireland (Scenario 2); and landfill in Ireland (Scenario 3).

2.1.1. Scenario 1: Co-processing in a cement kiln in Germany

Co-processing in a cement kiln requires that blade material is shredded into smaller parts, and then mixed with Solid Recovered Fuel (SRF), an alternative fuel made from mixed dry recyclables that are too difficult to separate and would otherwise go to landfill. SRF is used across Europe as a substitute for fossil fuels in the cement and power industries, and the preparation of SRF must be in compliance with specification CEN 15359 (European Committee for Standardization, 2011). The polymer portion of the blade acts as fuel to bring the cement kiln temperature above 850 °C, replacing a portion of fossil fuel. The temperature must then be brought up past 1450 °C (fuelled by fossil fuel), at which time the alumina-borosilicate and the calcium carbonate from the glass fibre portion both calcify, turning into alumina, silica, and calcium oxide, which are all required components of Portland cement. In this option, all of the waste is used in the process and nothing goes to landfill.

Neocomp is a certified disposal company located in Bremen, Germany, which offer reprocessing and utilization of GFRP. GFRP is collected, cut up, shredded and combined with other material to form SRF. Assumptions were made that the SRF + GFRP received no other processing other than the shredding, and the material was loaded loose into containers. The SRF is then sent to Holcim cement factory in Lägerdorf, Germany for use in the cement kiln. Neocomp guarantee 100% recovery of GFRP in their process, and incorporate GFRP into SRF destined for the cement kiln at a ratio of 50% GFRP to 50% SRF. This number is used to calculate material substitution in section 2.2.4.

According to an Irish waste management company, blades are cut on site into 1.5 m^2 size and transported in amounts of 6–8 tonnes in an articulated lorry to a receiving waste company. Blade waste is transported to one of the Southern or Eastern Irish ports, including Belfast, Dublin, Wexford or Cork, then shipped and transported to Bremen, for pre-processing. Blade waste is then shredded into <40 mm size pieces, metal components removed for recycling, and the remaining material combined with SRF. The SRF is transported to a cement manufacturer in Lägerdorf for co-processing in a cement kiln.

The LCA boundary of Scenario 1 includes transporting cut blades to the closest port, shipment to Europe, land transport from the port to the pre-processing site, processing into SRF, transport to the cement kiln, and finally, processing at the cement kiln. The fuel and aggregate that are replaced by the blade waste materials are included in the boundary as a negative contribution, as is the recycling of the metal components (Fig. 2).

2.1.2. Scenario 2: Co-Processing in Ireland

The co-processing in Ireland scenario is a hypothetical one. The data is based on energy used in the shredding process in Bremen, and transportation distances to Irish companies currently processing SRF. Blades would be transported in amounts of 6–8 tonnes in an articulated lorry to a pre-processing site in Ireland such as those operated by Glanway or Veolia. Blade waste would be shredded into <40 mm size pieces, metal components removed for recycling, and the remaining material combined with SRF. The SRF would then be transported to an Irish waste recycler such as Wilton Waste Recycling, Ballyjamesduff, County Cavan for processing into SRF. The SRF would then be transported to a cement factory such as Quinn Cement, Ballyconnell, County Cavan.

The Scenario 2 LCA boundary includes land transport to a pre-processing site in Ireland, processing into SRF, land transport to a cement kiln in Ireland, and finally the processing at the cement kiln. All fuel and energy consumed and emissions produced are included within the boundary. The fuel and aggregate that are replaced by the blade waste materials are included in the boundary as a negative contribution, as is the recycling of the metal components (Fig. 2).

In scenarios 1 and 2, the impact of the raw materials that were replaced by blade waste are subtracted from the impact of the blade waste co-processing steps. Therefore, credit is given for the prevention of the use of the fuel and raw materials, and as well as for the recycling of the metal.

2.1.3. Scenario 3: landfill in Ireland

Blades are transported in amounts of 6–8 tonnes in an articulated lorry to a receiving waste company, which transports them to the nearest landfill in Ireland. For simplification, transport directly from the site to the landfill is used in this study. The LCA boundary includes land transport to the landfill, and impacts due to the disposal of this material into landfill (Fig. 2).

2.2. Life cycle inventory analysis and data collection

Vestas V52 blades are made up of an outer skin and a core support structure, called spar caps and shear-webs. The shear-webs and skin are composed of a sandwich structure, made up of a core foam material (Sørensen et al., 2005) and composite outer layers (Fig. 3). The composite is a glass fibre mat impregnated with epoxy resin, manufactured using prepreg technology (Vestas Wind Systems, 2006a). In calculating the mass of each of the components of the V52 blade, assumptions had to be made due to the actual data not being available.

2.2.1. Metals

The metal components are the steel bolts for connection of the blade to the hub, and the copper lightning conductor and blade tip cap. The percentage of total mass varies from 2 to 8%, in various reports (Ancona and Mcveigh, 2001; Fingersh et al., 2006; Ortegon et al., 2013). An average of 5% is used to estimate the mass of metal in a blade.

2.2.2. Foam and adhesive

V52 blades contain a foam core in the skin and shear-web (Sørensen et al., 2005). The foam is assumed to be PVC or PET (Beauson et al., 2016; Skelton, 2017; Thomsen, 2009), and the adhesive is assumed to be Polyurethane. One calculation was found showing the combined percentage mass of foam core and adhesive as 9% (Fingersh et al., 2006).

2.2.3. GFRP composite

The remaining 86% of the blade is glass-epoxy composite material, of which 30–40% is epoxy and 60–70% is E-glass by mass

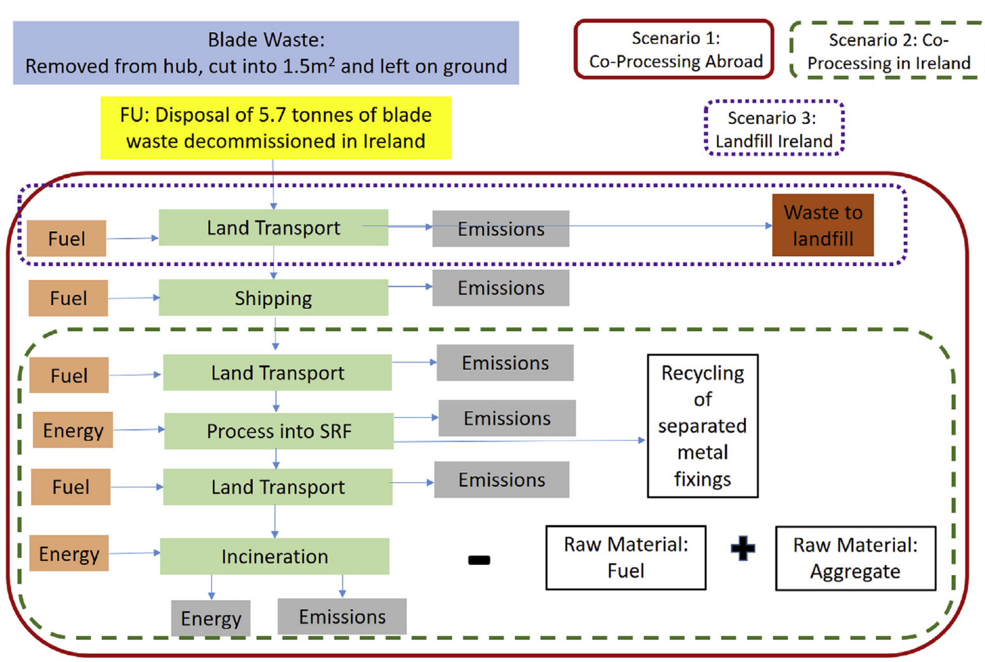

Fig. 2. LCA boundaries for scenarios 1, 2 and 3.

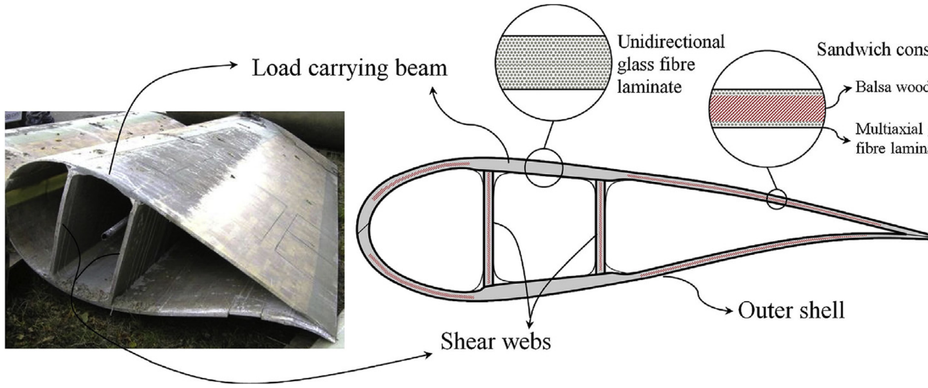

Fig. 3. Cross section of a typical blade (Beauson et al., 2016).

(European Committee for Standardization, 2011; Skelton, 2017). To calculate the total percentage of epoxy and E-glass, the average percentages of 35% epoxy and 65% E-glass were used, giving an estimate of 56% E-glass and 30% epoxy by mass in a V52 blade. Calculation of the mass of each component, with a functional unit of 5700 kg of blade waste, is shown in Table 1.

2.2.4. *Raw material substitution*

Environmental gains can be made by using waste material to substitute both fuel and raw materials in a process. In the case of the cement kiln, blade waste can be used to replace both coal for fuel, and the raw materials CaO, SiO_2, and $Al_2O_3 + Fe_2O_2$. As discussed earlier, the polymers in the GFRP serve as fuel replacement, and the components of the E-glass serve as raw material replacement. However, the proportions of components in the E-glass are not perfectly matched with the raw material requirements for clinker production, therefore blade waste must be added in certain proportions in order to meet the clinker requirements (Table 2). Cement requirements and E-glass component data come from Holcim Deutschland Group Environmental Data Document (Hahn, 2017).

In Bremen, blade waste is processed into SRF at a ratio of 50% of total SRF mass. This SRF with 50% blade waste is then shipped to the cement factory in Lägerdorf. Clinker for cement is made from approximately 20% SiO_2, 10% $Al_2O_3 + Fe_2O_2$ and 70% CaO (Hahn, 2017). The Lägerdorf site sits on soil that is 98% chalk, therefore, there is no need to use blade waste to replace CaO. However, the blades can be used to supplement the SiO_2 and $Al_2O_3 + Fe_2O_2$.

According to one study (Pickering, 2006), only 10% of the fuel input into a cement kiln should be substituted with polymer composite material, due to the presence of boron in the composites which slows cure time. Without exact knowledge of the amount of raw materials that are substituted using blade waste at the Lägerdorf site, a conservative 10% replacement value was used for SiO_2 and $Al_2O_3 + Fe_2O_2$, and for overall calculation of fuel substitution quantities (Table 3). A 50% replacement rate is run as a sensitivity analysis, as this is the maximum replacement rate that can be achieved due to the 50% blade waste incorporation rate into SRF. Regarding fuel replacement quantities, another study shows that each 1000 kg of blade waste can replace 600 kg of coal (Liu et al., 2019).

Table 1
Mass calculations for components in one V52 blade.

Component	% Total Weight	Total Mass in 5700 kg Blade Waste (kg)
E-Glass	56%	3192
Epoxy	30%	1710
Foam & Adhesive	9%	513
Metal	5%	285

2.2.5. *Transportation inputs*

A windfarm in the Northwest of Ireland is selected due to the number of V52 turbines in this farm that are nearing end of life. This farm has 12 V52 wind turbines which are due for decommissioning between 2021 and 2025, based on a turbine lifespan of 20 years. Table 4 contains transportation details for each of the three scenarios. Distances were calculated from Google Maps. Transportation from the site is done by an articulated lorry (truck). Each truck can take 6–8 tonnes of blade waste, therefore one truck would be needed to transport the 5.7 tonnes of V52 blade waste. Truck size and loading is standard in all of the scenarios, although travel distances varies.

For Scenario 1, blade waste is transported 200 km from the Wind Farm to Dublin Port, and then shipped to Bremen Port. The Port of Bremen is 916 nautical miles away, or 2.9 days sailing (Searoutes, 2019). The blade waste is taken directly to the pre-processing site, which is located within the Port. The receiving site completes pre-processing of the waste into SRF, and the SRF is transported 147 km to Lägerdorf.

For Scenario 2, blade waste is transported 86 km from the wind farm to the Wilton Waste Recycling, Ballyjamesduff, County Cavan for processing into SRF. The SRF is then transported 45 km to Quinn Cement, Ballyconnell, County Cavan.

In Scenario 3, blade waste is transported 120 km from the windfarm to the nearest landfill site of Derrinumera in County Mayo.

2.2.6. *Processing of blade waste*

In Scenario 1, the 1.5 m^2 pieces are shredded into <40 mm size pieces using a patented technology at Neocomp called the cross-flow mill with chain inlet (T.Hasse, Holcim/Lafarge, personal communication, 27th June 2019). The processing capacity is estimated at 150 kg/h with a total specific energy demand of 0.17 MJ/kg, based on the Wittman ML2201 granulator (Shuaib and Mativenga, 2016). In the EcoInvent database, the German low voltage energy mix was used in modelling the shredding process. The energy required to mix the material into SRF is negligible. In Scenario 2, co-processing in Ireland, the 1.5 m^2 pieces are be shredded into <40 mm^2 size pieces using a shredder at the Irish pre-processing site. The processing capacity is estimated at 150 kg/h with a total specific energy demand of 0.17 MJ/kg, based on the Wittman ML2201 (Shuaib and Mativenga, 2016). In the EcoInvent database, the Irish low voltage energy mix was used in modelling

Table 2
Material Components required for cement production (Hahn, 2017).

Material Component	Cement requirement	E-Glass components	% of each component in blade waste (56% of blade waste is E-glass)	% of each component in 10% SRF	% of each component in 50% SRF
CaO	65–75%	32–38%	19.6%	2%	9.8%
SiO_2	21%	52–58%	30.8%	3.1%	15.4%
$Al_2O_3 + Fe_2O_2$	6–11%	5–15%	5.6%	0.56%	2.8%

Table 3
Raw material replacement calculations based on a functional unit of 5700 kg of blade waste.

	Input Material	Raw Material Equivalent	Allowed percentage replacement	% raw materials substituted with blade waste	Raw material replaced with 5700 kg Blade Waste
10% Replacement of Raw Materials	1000 kg Blade Waste	600 kg coal	10%	600kg/1000 kg * 10% = 6% Substitution of Coal	342 kg coal
	1000 kg blade waste	560 kg E-glass	10%	560kg/1000 kg CaO = no substitution SiO_2 = 3.1% Al_2O_3 = 0.56%	0 kg CaO 177 kg SiO_2 32 kg Al_2O_3
50% replacement rate	1000 kg Blade Waste	600 kg coal	50%	600kg/1000 kg * 50% = 30% Substitution of Coal	1710 kg coal
	1000 kg blade waste	560 kg E-glass	50%	CaO = no substitution SiO_2 = 15.4% Al_2O_3 = 2.8% kg	0 kg CaO 885 kg SiO_2 160 kg Al_2O_3

Table 4
Transportation distances for all three scenarios.

Scenario	Transport Point to Point	Transport Type	Distance	5.7 tonnes * Distance (tkm)
1	WindFarm to Dublin Port	6–8 tonne truck	200 km	5.7 tonnes × 200 km = 1140 tkm
1	Dublin Port to Port of Bremen	Shipping liner	916 nautical miles (1696 km)	5.7 tonnes × 1696 km = 9667 tkm
1	Bremen to Lägerdorf	Standard Tautliner Trailers	147 km	5.7 tonnes × 147 km = 838 tkm
2	Windfarm to SRF Pre-processing site	6–8 tonne truck	86 km	5.7 tonnes × 86 km = 490 tkm
2	Pre-processing to cement factory	6–8 tonne truck	45 km	5.7 tonnes × 45 km = 256 tkm
3	Windfarm to Landfill	6–8 tonne truck	120 km	5.7 tonnes × 120 km = 684 tkm

the shredding process. The energy required to mix the material into SRF is negligible. To calculate the total power used during the shredding process in scenarios 1 and 2, take the functional unit of 5700 kg * 0.17 MJ/kg * 0.28 kWh/MJ = 271 kWh.

In Scenario 3, no processing is needed.

SimaPro software version 9.0.0.30 (PRé Sustainability, 2019) with the Ecoinvent V3.5 (Wernet et al., 2016) database was used for this study. All data in this study is secondary data from cited sources or EcoInvent. Any data without a citation was obtained from the EcoInvent Database of SimaPro using the APOS, S system model.

2.3. Life Cycle Impact Assessment selection

Life Cycle Impact Assessment (LCIA) is the assessment and characterization of various environmental impacts due to the product or process analysed. Assessments can be done at midpoint or endpoint categories. Many LCIA methods exist (Joint Research Centre, 2011, 2010). To narrow down the choice of methods, two parameters were chosen to screen the various LCIA methods:

1. Robustness in assessing Global Warming Potential (GWP)
2. Effectiveness in comparing two scenarios

For this paper, IMPACT2002+ was chosen for its special feature of comparative analysis, based on the second criteria of effectiveness in comparing two scenarios, its incorporation of the IPCC method, and its use of both midpoint and endpoint categorization (Humbert et al., 2014). Endpoint indicators, called Damage Categories, are used in this study. They include Human Health (Disability Adjusted Life Years of DALYs), Ecosystem Quality ($PDF \cdot m^2 \cdot y$), Climate Change (kg CO_2 into air) and Resources (MJ). Other categories include Normalization, which divides a damage category by the average impact of one European person per year, and Single Score, which is the summation of all of the normalized categories (Humbert et al., 2014). Normalized categories are unitless, and a default weighting factor of 1 has been applied to the Single Score output in this study. Single score outputs are used as a relative comparison only, and not as an absolute output of the LCA. A positive number in a category indicates a detrimental effect on the environment, with a higher number indicating a more detrimental effect. Negative numbers indicate a beneficial effect on the environment.

2.4. Sensitivity analysis

A One at a Time (Groen et al., 2014) sensitivity analysis was run on the main variables of transportation, shipment type, raw material substitution rate, and electricity mix, according to Table 5.

3. Results

The LCA results in this section are normalized and therefore unit-less, unless otherwise noted. Negative results indicate a negative, or beneficial, impact on the environment, with a more negative result being more beneficial.

Table 5
Variables included in the sensitivity analysis.

	Expected Lower Impact	Chosen Value	Expected Higher Impact
Raw Material Substitution Rate	50%	10%	N/A
Transportation	N/A	Transport, truck 10-20t, EURO4, 100%LF, default/GLO Economic	EURO1
Shipment Type	100% Full	Container ship ocean, technology mix, 27.500 dwt pay load capacity RER S	10% full Vessel Type
Electricity mix IE	N/A (PV not available in Ireland)	Electricity, low voltage {IE}| market for | APOS, S (Irish Electricity mix 2014)	N/A
Electricity mix DE	Electricity, low voltage {DE}| electricity production, photovoltaic, 570 kWp open ground installation, multi-Si | APOS, S	Electricity, low voltage {DE}| market for | APOS, S (German Electricity mix 2014)	N/A

3.1. Comparison of existing disposal methods

A comparison of the endpoint indicators of scenario 1 and scenario 3 show scenario 1 is less impactful to the environment than scenario 3 in all categories except Ecosystem Quality (Fig. 4).

For scenario 1, adverse effects on impact category Ecosystem Quality are predominantly due to transportation, but also include the electricity used in the shredding process, and shipping. The adverse impacts to Ecosystem Quality are not outweighed by the beneficial impacts of metal recycling, and the replacement of coal, Aluminium Oxide, and silica sand (Fig. 5). For the other three damage categories, the steel recycling, and replacement of the coal and Aluminium Oxide outweigh the impacts of the shipping, land transport and processing of the blade waste for SRF production.

3.2. Impacts of theoretical Co-processing in Ireland

Scenario 2 is calculated to be the least adversely impactful in all damage categories as compared to scenario 1 and 3 (Fig. 4). This is expected, as the theoretical co-processing in Ireland was modelled to match the existing process in Lägerdorf, with the exception of country specific electricity. Therefore the main differences between scenarios 1 and 2 is simply a reduction in shipping and transport, and any effects due to the local electricity mix. These differences result in a reduction of 119% in Human Health, 101% in Ecosystem Quality, 34% in Climate Change, and 58% in Resources (Fig. 4).

Using a single score output (Fig. 6), scenario 2 is 1007% more beneficial than scenario 3, and 78% more beneficial than scenario 1. Scenario 2 (co-processing in Ireland) is therefore determined to be the baseline disposal method against which future wind turbine blade repurposing ideas can be compared.

Quantification of the impacts of the process contributions of scenario 2 shows that all of the beneficial environmental impacts are due to the raw material substitution (Fig. 7). The negative impacts are due to the transportation and the shredding processes.

Table 6 lists the amount of impact in all endpoint categories for each of the different process steps. The total amount of impact is negative in all categories.

3.3. Impacts of transportation versus substitution rates

A higher level of raw material substitution should further reduce environmental impacts. Blade waste is incorporated into SRF at a rate of 50%, therefore theoretically up to 50% of the SiO_2 and Al_2O_3 + Fe_2O_2 can be replaced by blade waste. However, as mentioned previously, incorporation rates of greater than 10% might results in slower cement curing time (Pickering, 2006). This section compares varied substitution rates against transportation distances, to determine which has the greater environmental impact.

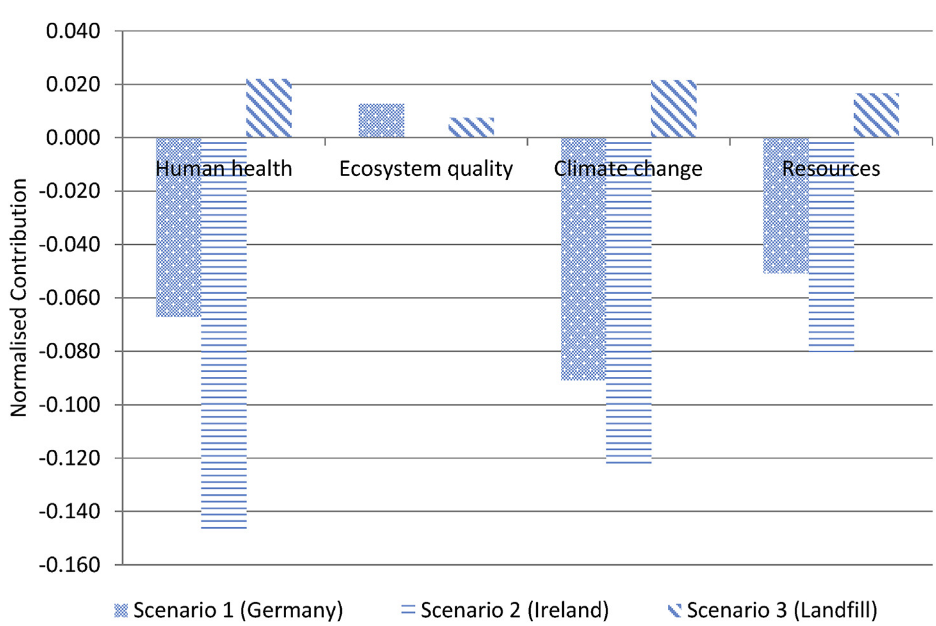

Fig. 4. Damage assessment of scenarios 1, 2, and 3.

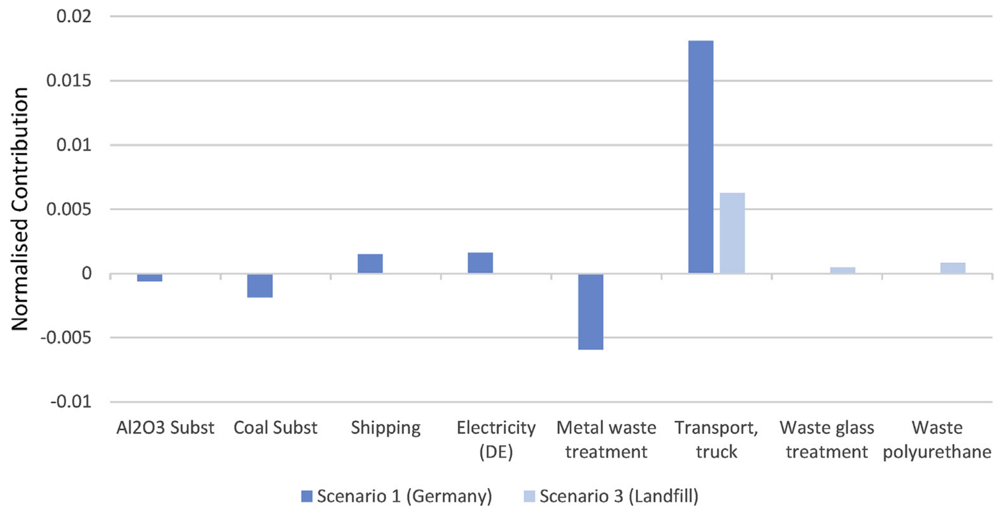

Fig. 5. Scenario 1 and 3 process contributions to impact category Ecosystem Quality.

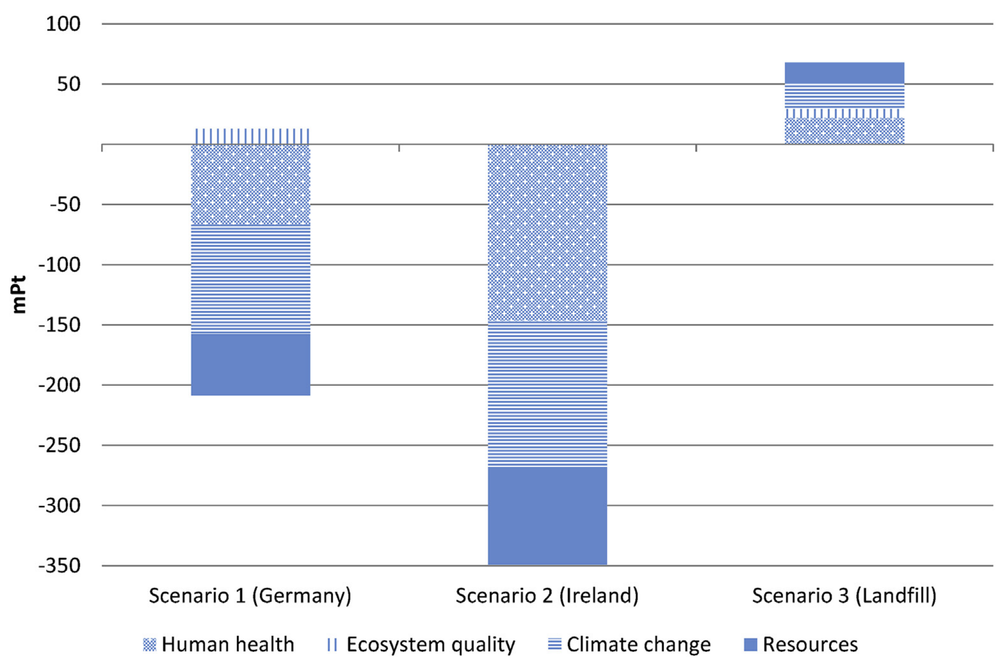

Fig. 6. Single Score damage assessment comparing scenarios 1, 2, and 3.

An increase in material substitution rates from 10% to 50% caused a beneficial impact to three of the four categories: Human Health (−360%), Climate Change (−393%), and Resources (−492%) (Table 7) leading to an average of 415% improvement to the environmental impact. Ecosystem Quality changes were negligible. The impact due to transportation was markedly less than the impact due to raw material substitution rates. Co-processing of Irish blade waste in Ireland rather than Germany, which requires less transportation, resulted in a beneficial impact to three of the categories: Human Health (−69%), Climate Change (−20%), and Resources (−33%) (Table 7) for an average of 41%. Overall, significantly more environmental gains can be achieved by increasing the substitution rate from 10% to 50% than by reducing transportation distances.

3.4. Sensitivity analysis

The results of the material substitution rate were discussed in section 3.3. A separate sensitivity analysis was run on the other process variables of transportation, shipment type, and electricity mix according to Table 5. A single score output is used to quantify the major effects due to varying the three inputs (see Appendix Figures A.1, A.2, and A.3). Varying truck emissions results in a 2% increase in impact. Varying shipment type results in an 8% increase with barge shipping. Varying electricity mix by using rooftop PV generation in Germany resulted in a 12% decrease in impact as compared to using the German electricity mix from 2014. However, an increase of 2% + 8% in impact due to using a truck with higher

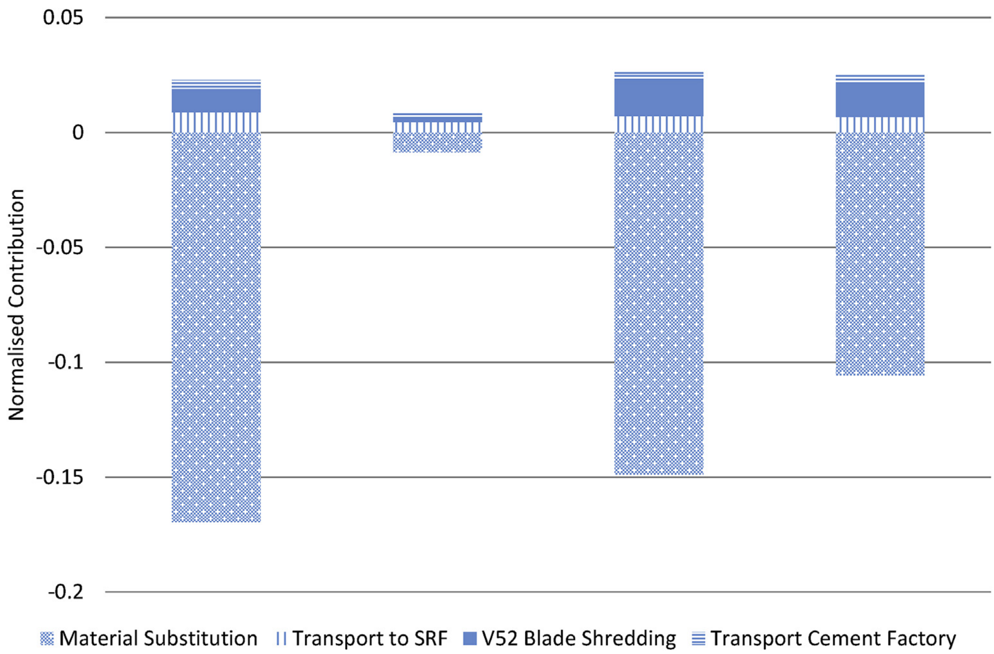

Fig. 7. Impact Assessment per process for scenario 2.

Table 6
Total damage assessment of scenario 2.

Damage Category	Material Substitution	Transport to SRF	V52 Blade Shredding	Transport Cement Factory	Total
Human health	−0.1696	0.0089	0.0094	0.0046	−0.1467
Ecosystem quality	−0.0087	0.0045	0.0016	0.0024	−0.0002
Climate change	−0.1488	0.0072	0.0159	0.0037	−0.1220
Resources	−0.1057	0.0067	0.0152	0.0035	−0.0802

Table 7
Comparison of transportation distance versus raw material substitution rate.

Damage category	Ireland 10% Substitution	Ireland 50% Substitution	Germany 10% Substitution	Germany 50% Substitution	Average Difference Transport	Average Difference Substitution
Human health	−0.147	−0.478	−0.067	−0.399	−69.43%	−360%
Climate change	−0.122	−0.531	−0.091	−0.500	−20.30%	−393%
Resources	−0.080	−0.386	−0.051	−0.356	−33.14%	−492%

emissions and barge shipping, or a reduction of 12% impact due to using PV generated electricity for shredding the blades in Germany did not change the results that Scenario 2 is less impactful than Scenario 1 or 3.

4. Discussion and conclusions

In this study, the environmental impacts of the disposal of Irish blade waste were quantified using Life Cycle Assessment. The study compared three possible ways of handling Irish blade waste: co-processing in a cement kiln in Germany (Scenario 1), co-processing in a cement kiln in Ireland (Scenario 2), and landfill in Ireland (Scenario 3). This is the first study to consider what is currently happening or what will likely happen in the near future, with Irish wind turbine blade waste. It confirms an earlier study of blade waste used in clinker production which showed the carbon footprint due to transportation has far less influence as compared to the beneficial impact of the raw material substitution, and it expands on this study by including current substitution rates and a full LCA (European Composites Industry Association, 2013). Other methods of GFRP recycling such as pyrolysis or grinding for cement fillers or composite reincorporation are currently not economically viable (Farinha et al., 2019; Palmer et al., 2009) and as such, are not yet utilized. Quantification of the impacts of the current method of disposal, and a critical analysis of near future disposal scenarios, is critical in order to begin to develop alternatives that are higher on the waste hierarchy (European Commission, 2017; Ierides et al., 2018), which are also quantifiably less impactful. This analysis can be used as a baseline comparison to assess potential repurposing solutions, to determine if a solution that is higher on the waste hierarchy is truly more environmentally beneficial than the current method of disposal.

Co-processing of Irish blade waste at a 10% material substitution rate in a German cement kiln was found to be six times better environmentally than depositing waste in an Irish landfill. Theoretical co-processing in Ireland at a 10% substitution rate was found to be is 1007% better than landfill in Ireland, and 78% better than co-processing in Germany. When the raw material substitution rate increased from 10% to 50%, German as well as Irish co-processing was beneficial to the environment in all categories. An increase in raw material substitution rate from 10% to 50% caused significantly more environmental benefit than a decrease in transportation distance. Therefore, additional work is needed to establish the maximum amount of material substitution that will still result in comparable clinker quality.

With the strong possibility of co-processing to be developed in Ireland if enough blade waste becomes available (Veolia, personal communication, 28th May), Irish co-processing at 10% replacement rate is chosen as the baseline scenario. However, there is nevertheless a significant concern with this disposal method in that the ease of disposal of blade waste in this fashion might de-incentivize repurposing, which is further up the Waste Hierarchy. The challenge, then, is to develop solutions that are clearly better both environmentally and economically, that will ensure the option of co-processing in Ireland is passed over for a more sustainable Irish alternative.

Further research is needed to establish the costs of co-processing in Ireland as compared to suggested repurposing solutions. Clearly, a repurposing solution must be viable in order for wind farm operators and waste management companies to choose such a solution over conventional disposal methods. Policy changes are needed that would require wind farm owners to post a decommissioning bond upon build completion, to cover the costs of sustainable disposal methods. Tax allowances and penalties may also be used to reward the utilization of solutions that are higher on the waste hierarchy. This could be achieved through an increase in the cost of landfilling and incineration of GFRP to match the approximate cost of co-processing. Finally, a directive similar to the End of Life Vehicle directive (European Parliament, 2000) should be put in place requiring 95% of composite material to be reused or recycled.

The environmental impact due to the disposal method of Irish wind turbine blade waste is most strongly affected by the amount of raw material substitution that can be realized when using the waste as substitute fuel and materials in clinker manufacturing. The limitations of this study therefore come from a lack of certainty as to how much raw material is actually substituted in the Lägerdorf cement factory, and how much might be substituted if blade waste is used in an Irish cement kiln.

More analysis of the LCIA methods could be carried out in order to determine the best method. Different repurposing applications may indicate different methods. Likewise, as economic data for repurposing applications becomes available, it may make sense to begin to use a method that includes more costing assessment, like Life Cycle Costing (LCC). In addition, an overarching framework that includes not only LCA and LCC, but social LCA (s-LCA) could be developed. The combination of LCA + LCC + s-LCA is called Life Cycle Sustainability Analysis (LCSA) (Gbededo et al., 2018; Valdivia et al., 2013). This could be combined with the United Nations Sustainable Development Goals (Maier et al., 2016; UN General Assembly, 2015; Wulf et al., 2018) to create a truly overarching, sustainable framework with which to assess disposal methods of Irish GFRP waste.

CRediT authorship contribution statement

Angela J. Nagle: Methodology, Investigation, Formal analysis, Writing - original draft, Visualization. **Emma L. Delaney:** Formal analysis, Writing - original draft. **Lawrence C. Bank:** Conceptualization, Supervision, Writing - review & editing, Project administration, Funding acquisition. **Paul G. Leahy:** Conceptualization, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

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