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Life cycle assessment of the use of decommissioned wind blades in second life applications

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ABSTRACT

53,000 tonnes of blade waste from on-shore wind farms will potentially be generated in Ireland by 2040. The recycling of blades, which are made from composite material, is costly and thus far no high volume recycling solution exists. Repurposing blades into second life structures is an alternative which is gaining in popularity, but has many challenges. Green Public Procurement has the potential to help drive demand for blade products in Irish public works. The Re-Wind project has generated a Design Atlas with 47 blade product concepts and these are screened for their ability to overcome repurposing challenges. Three Irish scenarios are developed based on this ranking, maximal utilization of the blade, and on the end customer. Life Cycle Assessment is used to determine the marginal environmental impacts of the raw material substitution provided by the use of blade material. Focusing on greenhouse gas emissions, an estimated 342 kg CO_2 e can be saved for every tonne of blade waste used in these scenarios. Blade substitution of steel products was found to provide the most impact, followed by substitution of concrete products. Although repurposing is unlikely to offer an end-of-life solution for all Irish blade waste, the use of 20% of this material annually would divert 315 tonnes of blade waste from landfill, as well as avoiding emissions of 71,820 kg CO_2 e. Green procurement has the potential to create a demand for repurposed blade products, which in turn could create jobs in high unemployment areas. Utilization of repurposed, local material could contribute to creating resiliency in supply chains. Both job creation and supply chain resiliency are essential for a post-Covid recovery in Ireland.

1. Introduction

Renewable energy generation is critical in reducing greenhouse gas (GHG) emissions. In Ireland, wind energy has been heavily relied upon for renewable energy capacity, with 85% of renewable electricity generated by wind in 2018 (seai.ie). Wind turbine design life is typically 20 years (Beauson, J. and Brøndsted, 2016; Elsam Engineering A/S, 2004; Jensen and Skelton, 2018; Marsh, 2017). Based on this 20-year lifespan, it is estimated that a cumulative total of 53,000 tonnes of blade waste from on-shore wind farms will be generated by 2040 in Ireland, peaking at just over 9,000 tonnes per year in 2037 (Delaney et al., 2021). As wind farms reach end of life, second life solutions for these turbines are needed.

1.1. Turbine end of life

Much of the turbine can be recycled or reused, such as the steel tower, batteries and magnets (Jensen, 2019). However, the recycling of blades, which are predominantly made from glass fibre reinforced polymer (GFRP) composite, is costly and no well-established, best practice exists on an industrial scale (Psomopoulos et al., 2019; WindEurope, 2020). Recycling of GFRP can be achieved through pyrolysis, a thermal recycling process which results in glass fibres of reduced strength (Cousins et al., 2019; Rybicka et al., 2016) or mechanical grinding, both of which are at a Technology Readiness Level (TRL) of 7 or higher (Rybicka et al., 2016; WindEurope, 2020). Another option is co-processing (or co-incineration) of the material in a cement kiln, which is used in Europe (Hanes et al., 2021; WindEurope, 2020). Of

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these three options, pyrolysis is clearly not economically viable for GFRP, due to the degraded quality of the resulting glass fibres when compared with the competing low cost to purchase virgin glass fibres (Oliveux et al., 2015). Both mechanical grinding and co-processing in a cement kiln require the blade to be shredded into small pieces (Hanes et al., 2021; Oliveux et al., 2015). In mechanical grinding, the shredded material is ground more finely and re-formed into fillers, or combined with resin to be made into panels (Cherrington et al., 2012; Hanes et al., 2021; Oliveux et al., 2015). Several companies are creating products out of this recyclate (Gees Recycling, 2021; Global Fiberglass Solutions, 2021; Reprocover, 2021), which can cost more than virgin material (Cherrington et al., 2012), and finding end users of the material can be challenging. Mechanical grinding applications are considered recycling, and do preserve some of the mechanical properties of the composite. At end of life, these second life products can be ground up again and made into third life products (Gees Recycling, 2021; Global Fiberglass Solutions, 2021), thereby contributing to a circular economy. In co-processing, the material is incorporated with other waste material, and sent to a cement kiln where the blade waste replaces a portion of the processing fuel and the raw materials (European Composites Industry Association, 2013). Co-processing in a cement kiln is used for the disposal of blade waste in Europe, which also allows for the recovery of embodied energy and materials (Ierides et al., 2018). However, in this application, all of the mechanical properties of the composite are destroyed, and there is no opportunity to recycle the material into third life applications (Chiesura et al., 2020).

Life Cycle Assessment (LCA) can be used to assess end of life options for blades. However, there have only been a few studies conducted thus far. A study of 52 LCAs of wind turbines showed that end of life impacts were only included in a few of these studies, and of these studies, all assumed landfill or incineration (Sakellariou, 2018). Another study found that co-processing of Irish blades waste in a cement kiln in Germany was less impactful than landfilling the blades in Ireland, from a blade waste disposal perspective (Nagle et al., 2020). A screening study showed that the use of a novel, recoverable resin in the GFRP material could offer 28% reduction in CO_2e due to the reuse of the resin and 90% of the glass fibres (Chiesura et al., 2020). However, this blade technology has not been implemented yet, and thus will not apply to existing blades. Finally, a 2020 study conducted by the Electric Power Research Institute (EPRI) using LCA and a Techno-Economic Assessment of blade recycling indicated that pyrolysis had the lowest environmental impacts (Gonzalez, 2020). However, the study did not appear to take into account any benefits due to raw material substitution as provided by the use of blade material in cement manufacturing.

Landfilling is an option but is becoming increasingly unpopular (Jensen and Skelton, 2018). Blades are extremely bulky and take up a lot of expensive space in landfills, leading to the banning of this practice in several European countries, and increased landfill fees in other countries (WindEurope, 2020). Finally, in interviews with decommissioning companies in Europe, several companies were choosing temporary storage of discarded blades over their immediate disposal (Everun Ltd, personal communication, December 3, 2020; Windtranz, personal communication, December 10, 2020; Rhenus Offshore Logistics, personal communication, January 12, 2021). This indicates that companies in possession of used blades are realising their intrinsic value and therefore prefer not to dispose of them at a cost, or are choosing to postpone the cost of disposal. These companies are all either actively looking for or working on, end of life options that are economically viable, or are confident that a solution is coming soon enough to justify the cost of storage and postponed disposal.

1.2. Repurposing blades

Repurposing blades into second life structures is an alternative which is gaining in popularity. Civic structures such as pedestrian bridges and transmission towers are being piloted by the Re-Wind Network (Alshannaq et al., 2021; Re-Wind Network, 2021; Suhail et al., 2019). Playgrounds, bicycle shelters, and furniture have been built through other projects (Adamcio, 2019; SuperuseStudios, 2012) and multiple bridges have been designed (Adamcio, 2019; Jensen and Skelton, 2018; Speksnijder, 2018). Like recycling, repurposing of discarded material substitutes virgin raw material and reduces its associated production, transportation and extraction impacts. Unlike recycling, however, the repurposing of waste into large structures typically requires far less processing which, as measured using LCA, can offer more environmental gains (Assefa and Ambler, 2017; Deeney et al., 2021; Nagle, 2020).

Repurposing of construction waste has many challenges that must be overcome. As examples, perceived lower quality of used materials and unknown residual structural properties (Fujita and Masuda, 2014), lack of end markets for the materials (Hopkinson et al., 2018), unfamiliarity with sourcing and using recycled products and unpredictable material availability (Shooshtarian et al., 2020), and uncertainty as to whether repurposing is truly better environmentally (Ruschi et al., 2020), are some of the challenges.

LCA is used to quantify the environmental impacts due to a process or product throughout its lifecycle (ISO, 2006) and can be used to assess waste diversion activities (Cherubini et al., 2009; Rigamonti et al., 2009). A waste diversion activity could be the use of discarded material, such as a wind blades, as a substitute to virgin raw materials. By clearly establishing system boundaries and functional equivalence, LCA can be used to measure (and compare) gains made through material substitution (Turconi et al., 2011; Vadenbo et al., 2017; Wang et al., 2017). Functional equivalence means two or more products are considered 'interchangeable alternatives for the fulfilment of a specific function' (Vadenbo et al., 2017). However, having an equivalent function does not guarantee that one product will, in practice, be chosen to replace another product. This outcome will depend heavily on market factors, but can be encouraged through green purchasing initiatives.

Green Public Procurement (GPP) is a European wide initiative that is expected to encourage repurposing of materials in the public construction sector. In Europe, the public authorities consume 14% of GDP on goods, services and works, which equates to €1.8 trillion annually (GPP4Growth Project, 2020), with Ireland's public spending averaging 10–12% of GDP (DECC, 2021). The motivation behind GPP is to focus this purchasing power on the promotion of resource-efficient goods and services. Ireland is one of nine countries participating in the Interreg program GPP4Growth, with the intent to incorporate reporting of green procurement efforts and expenditure in the government's annual report, as well as a revision of national green procurement guidelines and the development of a training plan for GPP at local level (GPP4Growth Project, 2020). In anticipation of stricter GPP requirements from the Department of the Environment, Climate and Communications (DECC), Irish local governments (County Councils), are beginning to look for procurement options with lower environmental impacts such as those that incorporate the repurposing of construction waste (JJ Doherty of Wexford County Council, personal communication, 13 May 2021). This new focus on GPP for public projects should create demand to repurpose locally generated construction waste such as discarded wind blades in public construction projects.

1.3. Measuring benefits

In construction, the GHG emissions of the lifecycle step 'Cradle to Gate' (A1-A3) is referred to as Embodied Carbon (Fig. 1). This step includes the raw material supply, transport, and manufacturing, which, in building construction, makes up half of the lifecycle carbon emissions (George, 2020), or 11% of total global GHG emissions. Embodied carbon calculators have become easier to use in recent years. For example, the Institution of Structural Engineers (ISE) in the UK has released a useful guide entitled "How to Calculate Embodied Carbon" (Gibbons and Orr, 2020). GHG emissions during the Use Phase (B6 Fig. 1) is also called Operational Carbon, which can be reduced through optimized design,

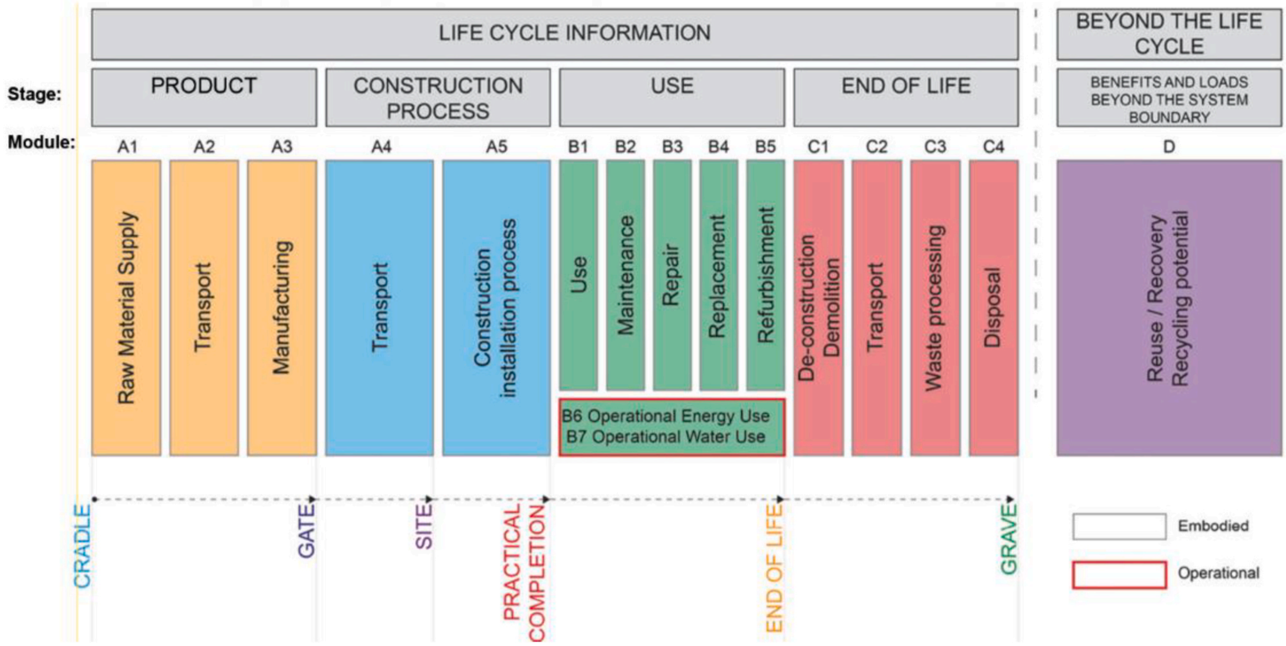

Fig. 1. Life cycle stages in a construction project (Gibbons and Orr, 2020).

and by decarbonising the use phase of energy supply. As operational carbon for a given structure reduces, its embodied carbon will grow in importance. The World Green Business Council's goal of 40% reduction of embodied carbon in all new buildings, infrastructure and renovations by 2030, and net zero by 2050, is essential to preventing a global temperature rise of 2 °C (World Green Building Council, 2020). Building sector impact indicators have become well established recently, with building LCA research progressively developing (Hossain and Ng, 2020). Given the many similarities in materials and techniques, the same indicators can be used to measure construction impacts (Coenen et al., 2021). Therefore, the sectors will be discussed interchangeably.

The World Green Business Council's report entitled 'Bringing Embodied Carbon Upfront' addresses ways to reduce embodied carbon. Fig. 2 shows that the vast majority of carbon reduction can be achieved through changes in the planning and design phases. Between 50% and 80% reductions can be made by 'building clever' and 'building less'. Repurposing of existing construction materials falls between these two descriptors, and the report does propose the mitigation of CO_2 through the reuse of materials. In fact, it suggests that we should start considering buildings as 'material banks' (Ghaffar et al., 2020; World Green Building Council, 2019).

Returning to life cycle assessment of material substitution, embodied carbon calculators can serve as a pre-screening method to discern the impacts of material substitution prior to conducting a full LCA. The ISE guide (Gibbons and Orr, 2020) includes CO_2 estimates for common and hard to abate construction materials (Table 1). Repurposing ideas can be

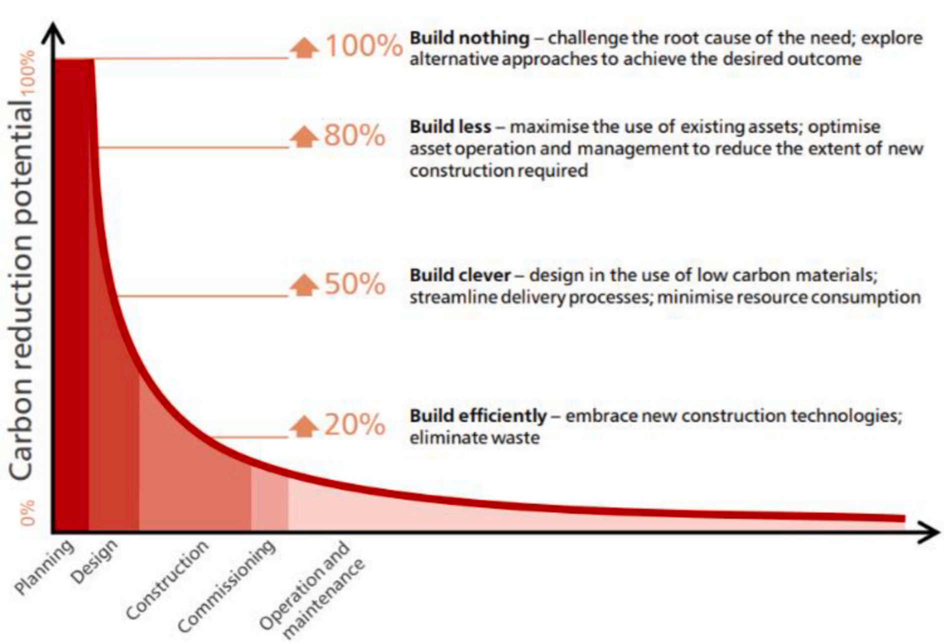

Fig. 2. Carbon reduction potential at various stages of a project (World Green Building Council, 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Common construction materials and embodied CO_2/kg (Gibbons and Orr, 2020).

Construction Material	CO_2/kg	Reference
Concrete, non-structural	0.113	Ref 15
Steel (structural sections)	2.45	British steel EPD Ref 19
Timber (excl. carbon sequestration)	0.437–0.512	Manufactured structural timber Ref 15

quickly pre-screened for impact using this table, and the top impact ideas further explored, or assessed with a full LCA.

This paper develops scenarios for the utilization of discarded Irish wind turbine blades which can be used to replace construction materials with high embodied carbon. The scenarios included consideration of public projects in order to capitalise on expected GPP requirements, as well as local applications. The specific research contributions include:

- Development of blade repurposing scenarios for full wind farms in Ireland, based on logistics, public acceptance, and carbon reduction efforts.
- LCA comparison of the scenarios
- Establishment of an indicator describing the amount of embodied carbon that can be reduced through the substitution of common construction materials by a given amount of blade waste.

2. Methods, scenarios, and LCA

2.1. Design Atlas Assessment

Repurposing ideas for decommissioned blades have been developed within the Re-Wind project and compiled in a Design Atlas (Bank et al., 2020). For this paper, the 47 Re-Wind Atlas concepts were assessed based on their ability to overcome the challenges discussed in the Introduction: they must be able to replace material that has high embodied carbon; they should be sufficiently low risk to allow adoption without regulatory delay, and the application should be simple and desirable enough for the re-processing to be viable in Ireland; the end use should be close to the location of the decommissioned farm, to reduce impacts due to transport; the amount of blade material and the part of the blade utilized should be balanced to optimize full blade consumption.

These challenges were distilled down to four criteria:

1. Amount of initial design and testing, and difficulty of fabrication
2. Ability to substitute material from Table 1: Construction Material Top GHG emitters
3. Feasibility of use in Ireland, including amount of blades utilized and GPP potential
4. Section of blade utilized

Criterion 1 – Amount of initial design including aesthetic alignment by architects, engineering testing and design, and difficulty of fabrication. If little processing beyond the cutting of the part in the field, and no testing was required, then a score of "low" was given. A score of "medium" would entail some design, testing, and moderate fabrication process. A score of "high" would require one or more of the blades to be tested structurally in order to validate the design and fabrication of a product, with a high level of fabrication also necessary.

Criterion 2 – Ability to substitute construction materials with high carbon intensity. A search was carried out of existing products sold in Ireland, and the materials used in those products were noted in the assessment table. Steel and concrete substitution were factored in as the most favourable.

Criterion 3 – Feasibility in Ireland, including amount of blades utilized and GPP potential. The authors assessed which of the products would most likely be used in Ireland based on what products were already for sale here, as well as estimating how many blades might be used in these products. Products were noted as being more likely to be used in public versus private sector applications, or both. Public applications were viewed more favourably, due to Green Public Procurement initiatives increasing their likelihood of adoption.

Criterion 4 – Part of blade utilized. 1 = root, 2 = mid-section, 3 = tip section. Many of the products required more than one section, but few required the full blade length.

The overall suitability of each idea was discussed and scored on a scale of 1–4, and this information helped to inform the scenario development. The full Design Atlas Assessment can be found in Appendix A.

2.2. Scenarios

The Re-Wind group has generated a 'dashboard' of Geological Information System (GIS) data (see Fig. 3), based on the work done by Delaney et al., 2021. The dashboard contains a compilation of blade material amounts by location and turbine type, based on an estimated 20-year turbine lifespan (Delaney et al., 2021). This allows for predicting supply and location of material well in advance of the estimated decommissioning dates. The dashboard allowed us to understand the number and type of blades to include in the study, and to establish a hypothetical wind farm location and remanufacturing site. For this study, we have narrowed the scope to wind farms that are 16 years or older. If we assume that most wind farms will decommission 20–25 years after they are built based on a design life of 20 years, this allows us to study the amounts and size of blades that are estimated to be available in the coming 5–10 years.

42 windfarms were identified on the island of Ireland that could potentially be decommissioned by 2023, based on a 20-year service life. Of these, approximately one-third were located in the province of Munster in the south of the country. Within Munster, other than one outlier that contained 70 turbines, the rest of the farms contained between one and 23 turbines, with an approximate average of 10 turbines per farm. Within the 42 farms, the majority had turbines with blade lengths between 13 and 35 m. Based on this information, we created a hypothetical representative wind farm located near Dunmanway close to the border of counties Cork and Kerry, consisting of 10 turbines with blades of 21.2 m each (Fig. 4). This hypothetical wind farm will be used to calculate the number of blades available for use, the length of the blades, and the transportation distances, all of which will inform the development of the scenarios, and will factor into the LCA.

The next step was iterative. Based on the results from the Design Atlas Assessment, the leading uses were first identified and overlaid physically on the section of the blade that they would utilize. Second, the end customer of the blade products was considered. We attempted to align all of the products in a scenario with one end user, such as Cork County Council. Therefore, ideas with high assessment scores, that were likely to be utilized by one customer, and that made use of each section of the blade, were organised into each of three scenarios. If a segment of the blade was grossly underutilized, or if a product did not fit the defined customer for a scenario, we returned to the design atlas to look for other uses for that segment.

2.2.1. Scenario 1: rural package: culverts, greenway bridges, and farm applications

Scenario 1 targets Irish government bodies responsible for rural development, as well as local farmers. Blade material is utilized as culverts and manholes, and as bridges (Fig. 5), thereby contributing to green public procurement by offering repurposed material for council works. The tip material will be remanufactured into cattle partitions and small grain partitioning walls for local farm use. The blades would be cut into root sections, 13 m middle sections, and 8 m tip sections before transportation.

Root section - Culverts or Manholes: The 0.2-m root section of all 30

Fig. 3. Dashboard depicting Irish wind farms that are 16 years or older (Delaney et al., 2021).

Fig. 4. An example of a blade approximately 21 m in length (photo credit Emma Delaney).

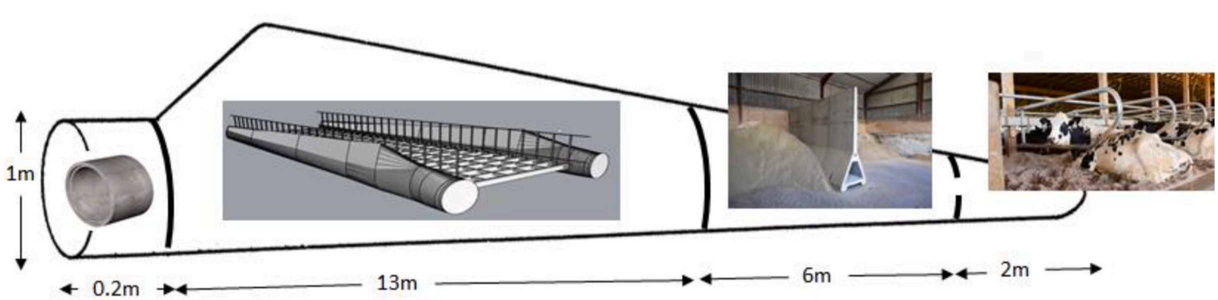

Fig. 5. Scenario 1 depiction of usage concepts per blade section.

blades will be cut off in the field and transported directly to a council yard for use as culverts or manholes. The root section can be secured together end to end for spanning longer lengths. This work can be done by the county council at the staging yard, and therefore no remanufacturing or transport to the remanufacturing site, is needed. The root sections can replace an amount of concrete for culverts.

Middle section - Girders for Pedestrian Bridges: 13-m sections will be cut, from the point at which the root section was removed up to 8 m from the tip. 28 of these sections will be used as girders for 14 pedestrian bridges with spans of 13 m each, for installation along a greenway in the south of Ireland. The last two blades will be used for structural testing. Transportation of the 28 × 13-m sections will be done by 12-m flatbed lorry with an allowed 1 m overhang. Transport is to an industrial site in North Cork where they are manufactured into bridge components, but not assembled. Transport of two of the prefabricated bridge components to the greenway is done by similar truck from the remanufacturing site to the greenway for assembly and installation. The 28 × 13 m blades will replace galvanised steel U-beams manufactured and transported from the UK.

Tip section - Cattle and Grain Partitioning: The 8-m tip sections can be cut and used as cattle partitions, and grain storage partitions. The last 2-m tip section of the blades would be used as cattle partitions, replacing an amount of 76 mm galvanised steel pipe. The remaining 6-m section would be used as small grain partitioning walls, replacing an amount of precast concrete walls. These pieces would be taken to the remanufacturing site in North Cork for fabrication.

2.2.2. Scenario 2: glamping package

Scenario 2 targets customers who would like to build or expand a holiday glamping business, such as farmers wanting to diversify their land, or private landowners interested in starting up a new business. Glamping refers to 'Glamourous Camping', offering campers high-end yurts, insulated pods, and many of the luxuries of home enclosed in a tiny hut. The Glamping market is growing in Ireland, and is expected to increase by 11% between 2019 and 2025 (Businesswire, 2020).

Scenario 2 assumes the receivers of the blade material will perform all of the manufacturing and assembly on site - no transportation to a remanufacturing site, or remanufacturing by an external vendor is necessary. This case relies heavily on two points: (1) The initial creation of a glamping pod prototype, with detailed instructions for constructing the pods at the campsite (2) Finding a suitable receiver who is skilled in handcrafting or can afford to hire a handcrafter. An agreement to purchase would have to include provisions for 'returning' unused material and offcuts. The blades would be cut into root sections, 12 m middle sections, and 9 m tip sections before transportation (Fig. 6).

Root section – Foundation Piles: The root section will be used as foundation formwork. A root section would be firmly placed in the ground at each of the four corners of the glamping pod, then backfilled with foundation grade material. The roots would serve to raise the pod slightly off of the ground.

Middle section – Roof for Glamping Pods: The middle sections would be cut into 12-m lengths for transport, and then cut into two 6-m length pieces upon arrival at the glamping site. The 6-m sections would then be cut lengthwise in a fillet cut, bisecting the shear webs of the blade to serve as the roofing (see Fig. 7). These sections would replace an amount of timber for the roof structure and coated sheet steel for water protection (Bank et al., 2019).

Tip section - Fencing: The final 8-m tip sections would be transported to the glamping site and cut for use as privacy barriers between sites and fencing, all of which would replace an equivalent volume of wood.

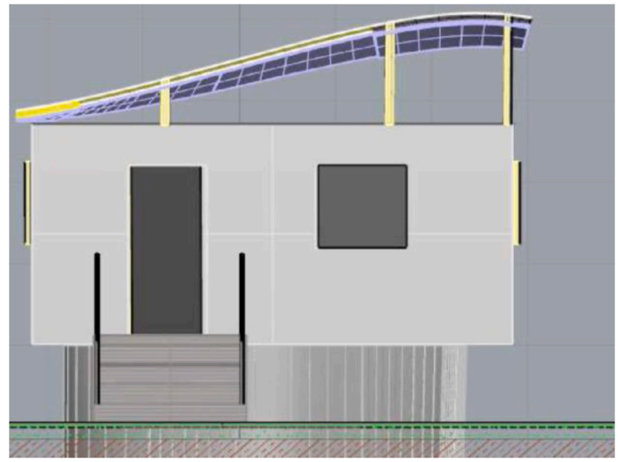

Fig. 7. Blade with 'fillet' cut, used as roof section (Bank et al., 2019).

2.2.3. Scenario 3: county council urban package. Planters, bus stops/bicycle shelters, bollards

Scenario 3 is aimed at urban local governments interested in GPP. It offers two different shapes of planters, roofing for bus shelters or bike racks, and material for posts or bollards (Fig. 8). All sections will be transported to the remanufacturing site where they will be cut and made into the products.

The blades would be cut into root sections, 12 m middle sections, and 9 m tip sections before transportation.

Root section - Round Planters: The root section will be made into round planters, replacing an amount of concrete.

Middle section - Bus stop/Bicycle Shelter: The middle 12 m will be cut into two 6 m sections, and fabricated into the roof for either bus shelters or bike shelters, both of which will have the same design. The blade will replace an amount of polycarbonate material, which is typically used for covering bus shelters.

Tip section – Oval Planters and Bollards: The first 6 m of the tip sections will be cut into 0.5–1 m sections and made into oval-shaped planters, which will replace an amount of concrete. The final 3 m of the tip will be cut into two 1.5 m sections, and made into posts or bollards, replacing an amount of new GFRP material.

2.3. LCA goal, system boundaries, and functional unit

The goal of this LCA is to assess marginal differences in environmental impacts through the substitution of construction material with discarded turbine blades. The system boundaries (Fig. 9) include the transportation of the blades to the remanufacturing site, the substitution of the production and transportation of raw material that would have been used to manufacture the same product, and the end of life

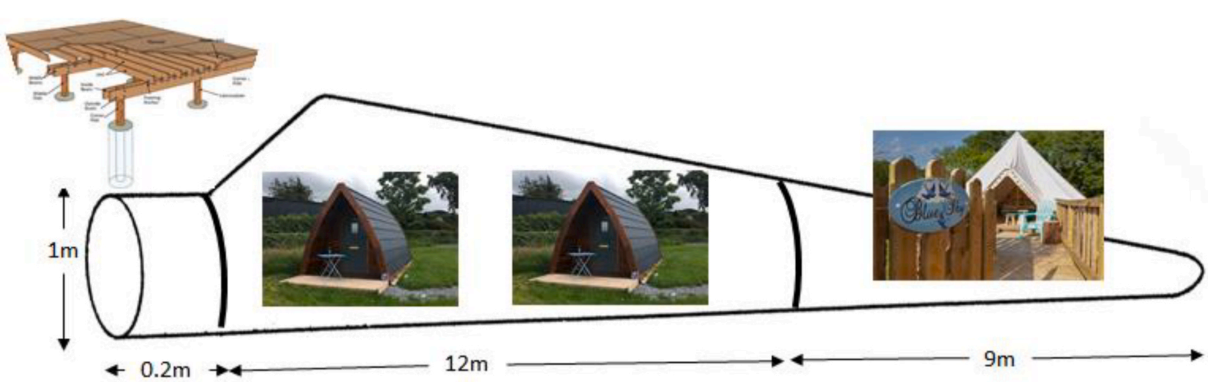

Fig. 6. Scenario 2 depiction of usage concepts per blade section.

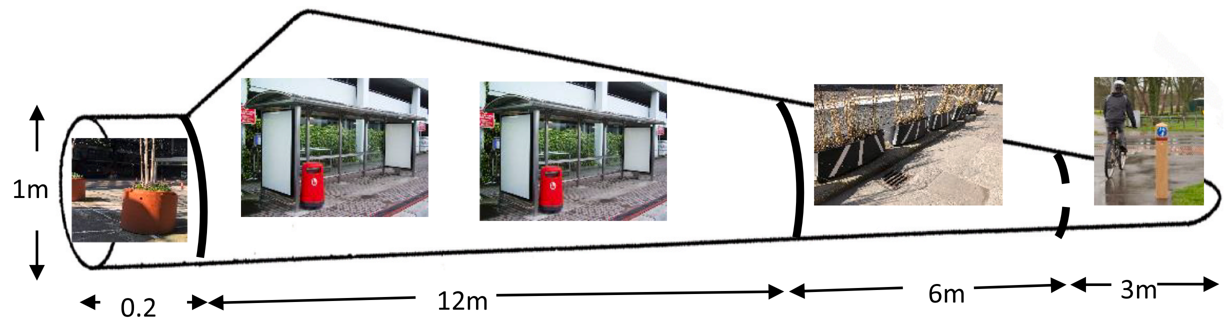

Fig. 8. Scenario 3 depiction of usage concepts per blade section.

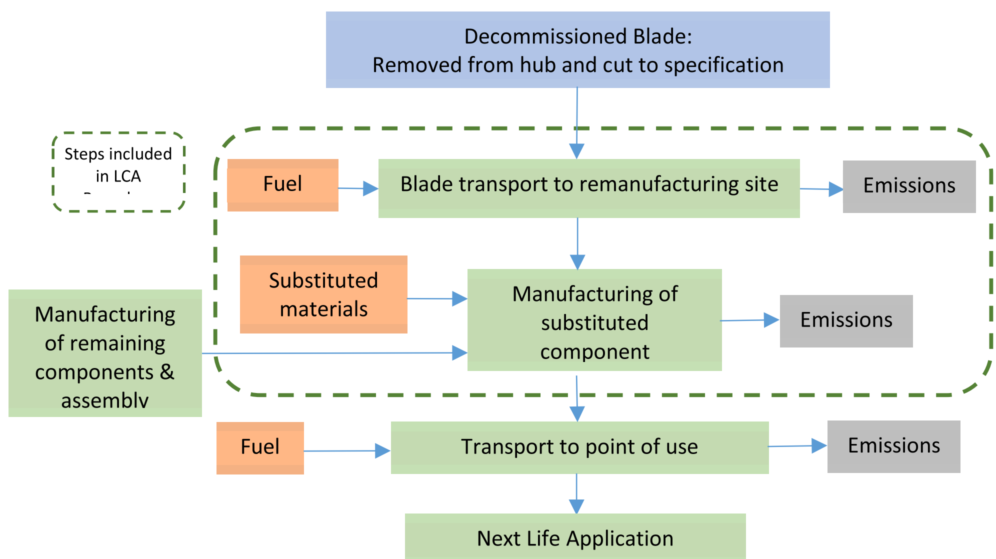

Fig. 9. LCA Boundaries for all three scenarios.

disposition of the blade material. The constrained system boundaries allow direct comparison of the material substitution only, and do not provide analysis of environmental impacts across the full production of these products.

The functional unit of an LCA allows a direct comparison of the environmental impacts of the function of a product or process. In this case, the functional unit allows for the comparison of repurposing an amount of blade waste, as described in three scenarios. The blade amount was selected based on the hypothetical wind farm of ten turbines with a total of 30 blades, each 21.2 m long. The temporal boundary was set to 60 years, based on a previous study of the use of the blades in a bridge application (Nagle, 2020; Suhail et al., 2019) combined with guidance on the design working life of a GFRP bridge in the UK (CIRIA C779, 2018). The timeframe is important when comparing the function of each substitution. For example, a polycarbonate roof for a bus shelter might have a design life of 10 years. If a blade section with an expected lifespan of 60 years were used instead, the blade material would replace six polycarbonate roofs over the course of its functional life.

The functional unit is: *The utilization for 60 years of 30 × 22 m GFRP blades, decommissioned at a windfarm in the Southwest of Ireland.*

The LCA software used in this study was SimaPro version 9.0.0.30 (PRé, 2019) with the Ecoinvent V3.5 database (Wernet et al., 2016). 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 Cut-Off, system model. Life cycle impact assessment and indicator selection followed the reasoning in Section 2.3 of (Humbert et al., 2014; Nagle et al., 2020). IMPACT 2002+ was selected for the impact assessment, and a combination of normalized Damage Categories and Single Score indicators were used. Single score assessments are used in high level comparisons, which is the goal of this study. 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. *Quantity survey of substituted materials*

In order to estimate the material substitution, existing Irish products that were identified in the Design Atlas Assessment were revisited. For each of the products in the three scenarios, material types and amounts were taken from online product specifications, and a quantity of substituted materials was calculated. Based on the design life of the existing product material, the quantity of materials was multiplied by a factor based on the functional unit time component. For example, the coated sheet steel for the roofing in the Scenario 2 Glamping Pod product has a design life of 20 years. Based on the functional unit of 60 years, three sets of coated sheet steel would be required. Therefore, a blade section that lasts 60 years would replace three quantities of the coated sheet steel. Calculations are included in Tables 2a–2c.

2.5. *End of life considerations*

The design of the products in each of the scenarios will follow circular principles including e.g., design for disassembly (Ghaffar et al., 2020; Pomponi and Moncaster, 2017). This includes, but is not limited to, ensuring products which utilize multiple materials are screwed together rather than nailed or glued such that components destined for

Table 2a
Scenario 1 material quantity replacement calculations.

Application	Blade Utilized	Material Substituted according to Functional Unit	Material calculations
Culverts	Root	Root section replaces 30 × 0.2 m x 909 mm OD pre-cast concrete pipe, 97 mm wall thickness. Pre-cast concrete is 2.4 tonnes/m^3. 60 year lifespan.	7,106 kg concrete
Bridge	Middle	Blades replace 203 × 133 × 25 galvanised UB girder. 13 m x 30 blades x 25 kg/m (density of U-Beams). 60 year lifespan.	9,750 kg galvanised steel
Cattle Partitions	Tip End	2 m tips replace 76 mm OD galvanised steel cattle partitions: 30 blades x 5 m length cattle partitions at 6.52 kg/m 60 year lifespan.	978 kg galvanised steel
Grain partition walls	Tip Mid	Pre-cast concrete partitions 6 m long, 0.6 m high, and 150 mm thick, at 2.4 tonnes/m^3. Doubling up of blades would give 15 walls (rather than 30). 60 year lifespan.	19,440 kg pre-stressed concrete

Table 2b
Scenario 2 material quantity replacement calculations.

Application	Blade Utilized	Material Substituted according to Functional Unit	Material calculations
Small Housing - Piling	Root	Concrete foundations 1 m diameter x 0.2 m deep x 30.60 year lifespan.	4.71 kg concrete
Small Housing - roofing	Middle	Wooden roof trusses: 30 blades × 2 pods/blade x 16 trusses/pod x 2.5 m lengths x 4 × 2 inch beams (0.1 m × 0.05 m) x 2 lifetimes. Poly-coated sheet steel: 30 × 2 × 2.5 m x 6 m × 0.0006 m x 2 lifetimes x 8,039 kg/m^3	14.4 m^3 wood 8682 kg organic coated steel
Fencing &; perimeter walls	Tip	Medium density wood with the same volume as the blade pieces. 9 m x average (1.088m–0.534 m)*.016 m thickness*30 pieces. 20 year lifespan No wood preservative required either, at 12 kgs/m^3 * volume of wood 20 year lifespan.	10.5 m^3 wood 126 kg wood preservative

different waste streams can be easily separated for repurposing or recycling. The bridge, glamping pod and bus shelter will be constructed such that the GFRP material can be separated from the decking of the bridge, the wall structure of the pod, and the uprights for the bus shelter. The grain partition walls and small house pilings will require the removal of the natural local filling material. The culverts, fencing, planters, and bollards are made solely from GFRP and will not require disassembly.

Recycling of GFRP in 60 years will likely have developed considerably, such that the epoxy and glass portions can be separated and utilized in a new application. Wind Europe anticipate that the development of thermal or chemical recycling of the blades will allow recovery of all composite components into 'chemical building blocks' (WindEurope, 2020). Quantifying the impacts or benefits of recycling the GFRP blade product material is outside the scope of this paper.

2.6. Comparison with Co-Processing baseline

Co-processing is the European composites industry preferred disposal option for blade waste (European Composites Industry Association, 2013), and was established in a previous study as a baseline disposal option against which other blade end of life options should be compared (Nagle et al., 2020). Therefore, in this study, co-processing/co-incineration of the blade waste was used as a baseline comparator. To determine if the repurposing scenarios are better environmentally than co-processing/co-incineration, material substitutions were calculated using the process established in (Nagle et al., 2020), see Table 3. In the current study, we assumed that 100% of the blade would be turned into cement clinker, rather than the 10% or 50% substitution discussed in Nagle et al. and that CaO would be included in the substitution calculations. The functional unit remains the same as the scenarios in this study.

Table 2c
Scenario 3 material quantity replacement calculations.

Application	Blade Utilized	Material Substituted according to Functional Unit	Material calculations
Round Planters	Root	Root section replaces 30 × 0.2 m x 909 mm OD pre-cast concrete pipe, 97 mm wall thickness. Pre-cast concrete is 2.4 tonnes/m^3. 60 year lifespan.	7,106 kg concrete
Bus Shelters, Bike Racks	Middle	30 sections x 3 cuts x 1.5 m wide x 4 m bus shelter roofs made from polycarbonate. Bus shelter roof is curved: a roof with 1.5 m depth results in an arc length of 1.7 m. Assume 8 mm polycarbonate thickness. Density 1.22 kg/m^3. Lifespan of 10 years.	35.8 kg polycarbonate
Oval Planters	Tip End	30 × 6 m tip mid-section replaces oval shaped concrete planter perimeter 1.764 m x 0.05 wall thickness. Pre-cast concrete is 2.4tonnes/m^3. 60 year lifespan.	38,102 kg concrete
Posts/Bollards	Tip Mid	Replacement of GFRP wood effect material for cycleway signage. Replacement of 30 × 2 × 1.5 m x .04m^2 posts. GFRP density estimated at 1.8 kg/m^3 60 year lifespan.	6.48 kg GFRP

3. Results

The LCA results in this section are normalized and therefore expressed as unit-less 'Points', unless otherwise noted. IMPACT 2002+ v.2.15 impact assessment was used, where the damage factor reported in EcoInvent are normalized by dividing the impact per unit of emission by

Table 3
LCA Inputs for co-processing based on a functional unit of 45,000 kgs of blade waste (Nagle et al., 2020).

Input Material and Processing	Raw Material Equivalent	% raw materials substituted	Raw material replaced & processing required
1,000 kg blade waste	600 kgs coal	600 kg/1,000 kg = 60%	27,000 kg of coal
	560 kg calcium oxide, silica, aluminium oxide (due to 56% E-glass and constituents in same proportion)	560 kg of raw cement material per 1000 kg of blade material	25,200 kg of raw cement material
		Cement raw material ratios:	
		63% CaO	15,876 kg CaO
		21% SiO_2	5,292 kg SiO_2
		5%Al_2O_3	1,260 kg Al_2O_3
Steel Recycling	5% of blade is steel	N/A	2,250 kg of steel
Shredding	0.17 MJ/kg	N/A	7,650 MJ required for shredding

the total impact of all substances of the specific category for which characterization factors exist, per person per year (for Europe) (Humbert et al., 2014). Negative results indicate a negative, or beneficial, impact on the environment, with a more negative result being more beneficial. The term for a negative impact will be 'beneficial'. A positive number indicates added environmental burdens, and will be further referred to as a 'detrimental' impact throughout this section.

A single score assessment of each of the scenarios indicates which of the substituted materials contributes the most impact. In scenario 1 (Fig. 10a), the substitution of an amount of galvanised steel (−3.9) is 7 times more beneficial than the replacement of an amount of concrete (−0.5). Transportation is detrimental (+0.25), but contributes only 5% of the detrimental impact as compared to the overall beneficial impact. In scenario 2 (Fig. 10b), steel replacement (−4.9) again is the most beneficial, followed by the substitution of sawn softwood (−1.4), then concrete (−0.5). The replacement of wood preservative offers only small overall benefits (−0.1). Scenarios 2 has no detrimental benefits due to transportation, as the blade material is modelled to be delivered directly to the point of use. In scenario 3 (Fig. 10c), substitution of precast concrete is the most beneficial (−0.9), with polycarbonate (−0.07) and GFRP (−0.015) replacement lower. Transportation is the same as Scenario 1 (+0.25).

Fig. 10. d compares all three scenarios and co-processing using the single score indicator, which is a normalized calculation of the four damage categories of Resources, Climate Change, Ecosystem Quality and Human Health. Overall, co-processing offers the most environmental benefits, the majority of which comes from the damage category of 'Resources', which includes the impact category of mineral extraction. Scenario 2 offers the greatest benefits of the three scenarios at −7 points, followed by Scenario 1 at −4.2 points, which is primarily a factor of the amount of steel that was substituted in both.

Scenarios 1 and 3 included travel from the windfarm to a remanufacturing site located 81 km away. However, in practice, the distance that material from wind farms in the north of the country would need to travel would be much longer. To determine the impact caused by an increase in transportation distances, a sensitivity assessment was conducted (Cucurachi et al., 2016). For Scenarios 1 and 3, transportation was increased to 514 km, the distance between the northernmost wind farms near Coleraine, Northern Ireland and the southernmost industrial estate location near Cork City, Republic of Ireland. Scenario 1 impacts became less beneficial by 28%. Scenario 3 impacts increased by 150%, causing this scenario to become detrimental environmentally. Varying the transportation distance for Scenario 3, we found that 371 km was the distance at which Scenario 3 became environmentally neutral.

Returning to the consideration of embodied carbon, we can calculated how much GHG, or CO_2 equivalent (CO_2 e) abatement can be achieved by focusing on the LCA damage category of 'Climate Change'. A negative value in this category indicates an amount of marginal CO_2 e reduction. If we consider a situation where 10 blades were allocated to each of the three scenarios, we can begin to estimate an amount of CO_2 e

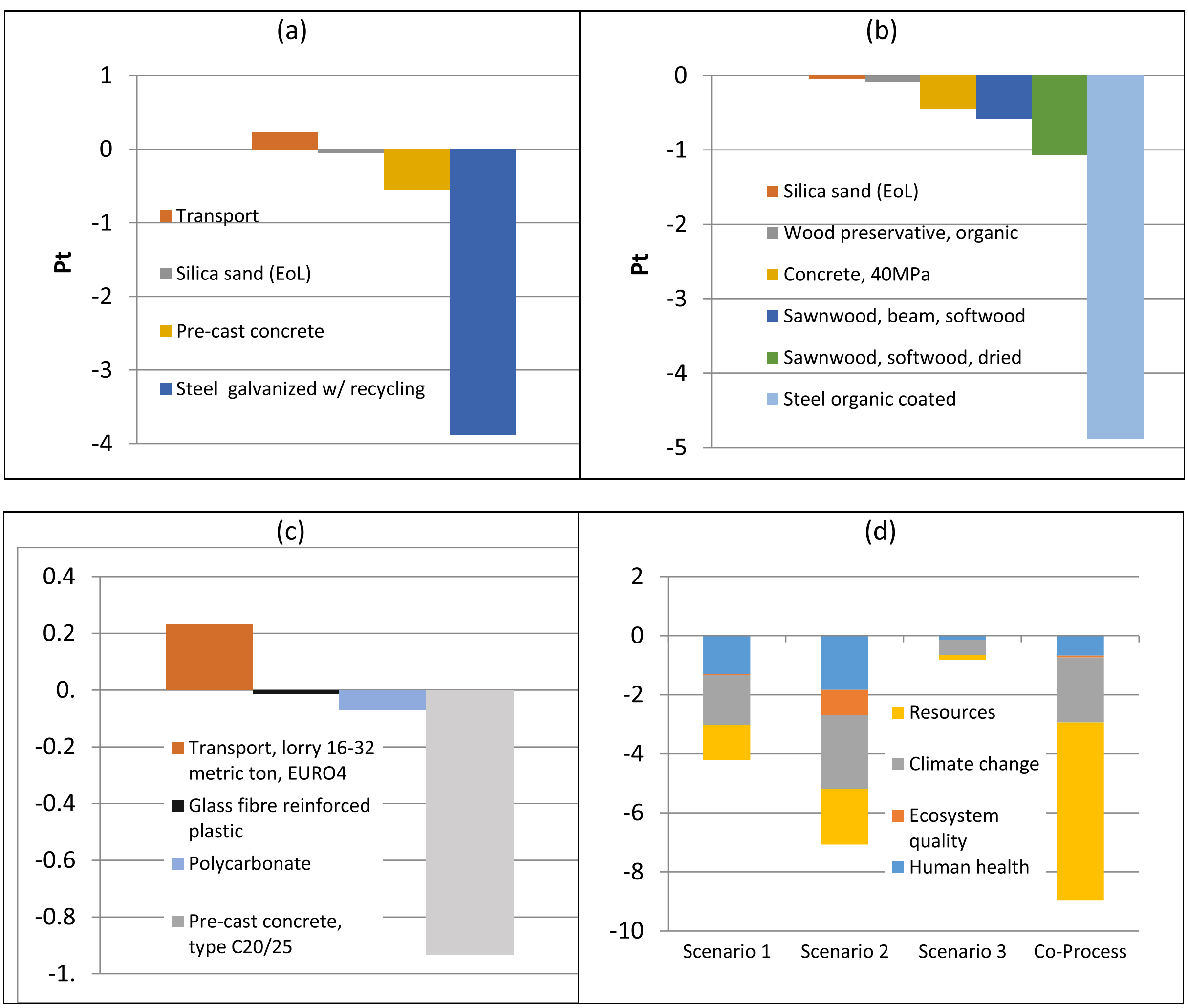

Fig. 10. Process contributions per scenario: (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, and (d) Single score assessment of the three scenarios compared to co-processing.

reduction that can be achieved by substituting raw construction materials with a tonne of blade waste (Table 4).

If 30 blades weigh 45 tonnes, then an estimate of 342 kg CO_2 e can be reduced for every 1 tonne of blade waste that is utilized in these scenarios, which is equivalent to 3,115 km driven in an average Irish vehicle (SEAI, 2018).

4. Discussion

The substitution of materials with high embodied carbon through the utilization of discarded blade material offers potential environmental gains. Substitution of steel products, such as polymer-coated steel roofing, offers the most environmental gains. This is due partly to the high embodied carbon of steel, but also due to sheet steel having a shorter lifespan than other construction materials such as concrete or steel girders, and thus requiring more frequent replacement. Further research in this area could include finding other steel applications to substitute with blade material, as well as other materials with lower embodied carbon that require more frequent replacement, such as polycarbonate roofing material or wood.

Co-processing was established as the baseline scenario in the Re-Wind project for the environmental comparison of repurposing scenarios (Nagle et al., 2020). It is interesting to see that in this case co-processing, despite being lower on the EU Waste Hierarchy (European Commission, 2017; Ierides et al., 2018), actually appears more immediately environmentally beneficial than repurposing of the blades, as calculated using LCA within the defined boundaries and assumptions set forth in the study. However, repurposing the blades into second life applications allows the material to potentially go on to a third, fourth or fifth life application, the final of which could be recycling or co-processing. The choice then is between an EoL disposal that is lower on the waste hierarchy but appears to be immediately more beneficial, considering the limitations and uncertainties of the calculations, or trusting in and subscribing to the circular economy approach, whereby keeping material in circulation for as long as possible may have more long term benefits. Second life design should therefore consider what subsequent life applications might be available and economically viable when those products are discarded, and the environmental impacts of these applications (Joustra et al., 2020), as illustrated in Fig. 11 above. Keeping the blades in use for longer may also allow time for more circular recycling technologies to be developed such as thermal or chemical recovery of the component, with the help of new policy measures.

One of the barriers to repurposing is unpredictable material availability. 'Stockpiling', or consolidation of the blades would be an option, if kept within current waste management regulations. If a blade 'aggregator' can show intent to re-use the material as defined in the Waste Framework directive under Article 3 (12) 'Prevention' (European Commission, 2008), then the blades may be kept out of the waste regime. If the material has entered the waste regime, the EPA End of Waste process requires demonstration of a market for the material in order to be de-classified as waste (DCCAE, 2020; EPA, 2020). Legal aggregation may solve the problem of unpredictable material availability for repurposing initiatives by ensuring a consistent supply of end of life blades. In addition, projects could be prioritized based on advance knowledge of suitable material supply, in order for economic and logistical concerns to be better addressed.

Table 4
Combination of three scenarios kg CO_2 equivalent per process input.

LCA Input	Kg CO_2 e
Transport, lorry 16–32 ton	397
Sawnwood, softwood, dried	−440
Concrete, 40 MPa	−617
Pre-cast concrete type C20/25	−2,826
Steel hot dip galvanised, w/recycle	−4,685
Steel organic coated/EU	−6,845
Polycarbonate & GFRP	−328
Total of all processes	−15,300
Total kg CO_2/Functional Unit	**−342 kg CO_2/tonne**

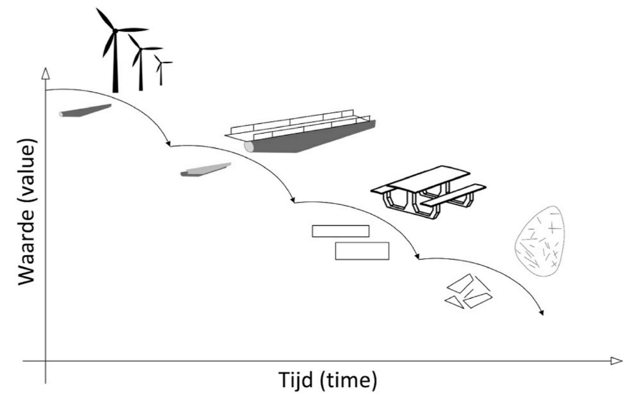

Fig. 11. Illustration of the time and value aspects of multiple repurposing of wind blades (Joustra, 2019).

Other repurposing barriers included the perceived lower quality of used materials, end-user unfamiliarity with sourcing and using recycled products, and unknown residual structural properties. For repurposing of these materials to take hold, awareness and perceptions of waste material must change. Low risk uses in public settings, such as planters and pedestrian bridges, can be advanced through GPP or similar initiatives in order to build confidence and familiarity with reused material. Brexit and Covid-19 combined to interrupt the construction material supply chain, causing what is assumed to be temporary shortages and price increases (O'Halloran, 2021; RTE, 2021). This sourcing interruption in the building sector could create awareness of a greater need for resiliency in the current supply chain, which potentially could increase motivation for repurposing of local materials. Already, the European Committee on Industry, Research and Energy is calling for the reuse of material as a means to support the diversification of access to critical raw materials, in order to bolster supply chain resiliency (DE VET et al., 2021).

In order for blade product usage to increase through GPP, local authorities will need to be open to considering alternative tenders as part of the public procurement process. An effort would have to be undertaken to educate public workers about the benefits of repurposing, so that repurposing might be specified in the tendering process. To maximise the benefit of such material repurposing, it should replace virgin materials used in 'hard to abate' industries, such as steel and cement production, and should also reduce associated transportation impacts by local sourcing (Energy Transitions Commission, 2018). Similar education for suppliers of public works, such as contractors bidding on full greenway projects, would increase the awareness of repurposing potential among contractors and sub-contractors of public works. Use of the generic calculated carbon abatement number of 342 kg CO_2 e per tonne of blade material, or independent waste and environmental impact diversion certifications, could help contractors and public workers to assess the sustainability of blade products. Finally, by collaborating with designers and engineers who supply public works, more applications for repurposed public products could be developed.

Repurposing is unlikely to utilize all of the blade material in Ireland. The industry body Wind Energy Ireland has estimated that a significant number of wind farms will start to be decommissioned in 2023. The Re-Wind dashboard estimates that there will be 2400 turbines on the island of Ireland that are expected to decommission between 2023 and 2039, peaking at 370 turbines in 2037. This amounts to an average of 150 turbines or 450 blades per year, with lengths between 23 m and 55 m, increasing proportionately from 2023 to 2039. To use all of these blades in Ireland in one year, distributed equally between all scenarios, a large number of products would have to be built. Table 5 is an estimation of

Table 5
Quantity of products required to utilize average annual blade waste amounts in Ireland from 2023 to 2039.

Application	Use of 1047 blades between 3 scenarios	Estimation of feasibility of each application per year
Culverts	75 m of culverts	Fully Feasible
Bridge	75 bridges	Would require 225 km of greenways to be built per year. 30% feasible
Commodity Item: Cattle Partitions	150 partitions	At 70 head of cattle per farm, this would outfit 2 farms. Fully feasible
Commodity Items: Grain partition walls	75 grain partition walls	30% feasible
Small Housing – Piling	37 pilings	Would require 9 tiny homes. Fully feasible
Small Housing – roofing	300 glamping roofs	10% feasible
Fencing & perimeter walls	1,350 0.2 × 1 m fence pieces	50% feasible
Commodity Items – Planters	150 one metre high planters	20% feasible
Bus Shelters, bike shelter	450 bus or bike shelters	10% feasible
Commodity Items – Planters	900 one metre high planters	10% feasible
Commodity Items – Signage	300 bollards	20% feasible

the number of products, as well as the feasibility of utilizing the amount of blade material in each application.

If 20% of the average yearly amount of blade material were repurposed, which amounts to 90 blades per year, then 135 tonnes of blade waste would be diverted from landfill, as well as 30,780 kg CO_2 e emissions.

Transportation does have a significant impact on the overall environmental impact, particularly in scenarios or uses in which there is a small marginal benefit. This supports the idea that waste material should be used as close to its source as possible. Exporting of blades should be considered only when substituting materials with shorter lives and longer embodied carbon, such as steel products.

Creating repurposed blade products could open up training in a very new field in Ireland. The new skills would require expertise in GFRP material handling, as developed within both Irish composites manufacturing companies and wind turbine maintenance companies, combined with bridge or civic structural construction skills. Training to combine these areas of expertise could be developed and provided through public efforts for re-skilling workers. In addition to the creation of the demand for a new skillset, a UK report has shown that the development of additional recycling capacity tends to create jobs in more rural, or high unemployment regions, as well as more mid-level jobs (Morgan and Mitchell, 2015). This could further contribute to a post-Covid recovery for Irish employment.

Overall, each of the three scenarios have advantages and disadvantages. Scenario 1 could be utilized by communities in close proximity to the decommissioned wind farms, further reducing the impacts of transporting blades further afield. Some rural communities in Ireland have been opposed to wind farms in their region, and the use of this material to benefit these communities could be viewed as a small compensation. The bridge and culvert applications have the strongest GPP potential of the three scenarios, and, as displayed in Table 5, this scenario has the highest overall feasibility for the utilization of blade material. Scenario 2 displays the most amount of environmental gain due to the substitution of sheet metal. The DIY (Do-it-yourself) nature of this scenario could empower small business owners to engage with the circular economy for the first time through self-building of glamping pods with waste material. However, this scenario has little GPP potential and likely would use less blade material than scenario 1. Finally, scenario 3 has the least environmental benefits and the lowest expected utilization of blade waste. However, the urban setting of this scenario means that many more people would be exposed to any product that was built. Therefore, scenario 3 has the highest potential for raising awareness of the benefits of repurposing.

Future research should aim to establish detailed costs for many of the aspects of this research: First, the diverted cost of what would have been the end of life disposal of the blade, such as landfill in Ireland or transport to Germany for co-processing; Second, marginal costs of producing blade products rather than using raw materials; Third, determining the costs and benefits of exporting Irish blade waste; Fourth, estimating the value of the waste diversion certification to wind farm owners. To round out this research into a sustainability assessment, more work should be done on the implications for job creation through the use of waste material.

Finally, waste policy will be key to spurring on repurposing in Ireland. Wind Europe has called for a ban on the landfilling of blades by 2025 (Bloomberg, 2021). If a landfill ban does indeed come into effect across Europe, Ireland will have to choose amongst the options available: co-processing, expensive recycling, or repurposing. Repurposing may become the most favourable option if recycling is still not economically viable, and co-processing is discouraged due to circular economy efforts.

5. Conclusions

The key findings were that the substitution of steel products offered the most environmental benefits, as measured in this LCA. The substitution of sheet steel, with a design life of 20–30 years, was particularly beneficial when assumed that the blade material would last 60 years, thereby replacing two quantities of the steel. Concrete substitution was also beneficial, although less so than steel. The substitution of polycarbonate and GFRP material was only somewhat beneficial, whereby the benefits would be cancelled if the blade material had to travel more than 370 km. An average GHG abatement amount per tonne of blade waste utilized in repurposing applications, within the boundaries and calculations in this LCA, was found to be 342 kg CO_2 e/tonne blade waste.

Repurposing is unlikely to utilize all of the blade material in Ireland. However, repurposing 20% of the Irish blade material would displace 135 tonnes of blade waste from landfill and 30,780 kg CO_2 e emissions per year. A market for these products, particularly products required for public works, could be bolstered by GPP policies. Rural jobs could be created combining the skillset of structural engineers with turbine repair technicians.

Future research should aim to establish cost for many of the aspects of this research including diverted cost of landfill, marginal costs of producing blade products rather than using raw materials, and estimating the value of the waste diversion certification to wind farm owners. Finally, more work should be done on the implications on rural job creation and improved supply chain resiliency through the repurposing of waste material.

Credit author statement

Angela Nagle: Conceptualization, Data curation, Methodology, Investigation, Formal analysis, Writing. **Paul G. Leahy**: Conceptualization, Supervision, Project administration, Funding acquisition, Writing – review & editing. **Gerard Mullally**: Conceptualization, Supervision, Project administration, Funding acquisition, Writing – review & editing. **Niall P. Dunphy**: Conceptualization, Supervision, Project administration, Funding acquisition, Writing – review & editing.

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. Design Atlas Assessment

Application	Initial Design, Testing & Fabrication	Material Substitution	Feasibility in Ireland, including amount of blades utilized and GPP potential	Blade Utilized (1 = root, 2 = mid, 3 = top)	Discussion of Suitability	Overall Rank
Ring/Tank	low	Concrete, Steel	Private farmers; high feasibility	1	Potential for no re-manufacturing which means items can be taken directly from the wind farm; concrete and steel substitution	4-high
Culverts	low	concrete	County Council use, or Farmers; med to high use for new construction projects	1	Place end to end for longer culverts; GPP; concrete substitution	4-high
Bridge	high	Steel	Public and private; High acceptance; high potential for blade utilization for greenway bridges	2	High interest; pilot project underway in 2021; med-high utilization of blade waste; GPP; steel substitution	4-high
Small Housing - Piling	med	concrete	Root sections could be used as foundations at the four corners of a tiny house for glamping	1	Excellent potential for full blade utilization with the root section as foundation which substitute some concrete, mid-section as roofing and tips as barrier walls or picnic tables for small holiday homes (glamping). Shelters along cycle-ways, bike shelters, and farm use as well.	4-high
Geo Retention	low	Gabions, concrete, stone	Public and private; mid utilization of waste, better acceptability in urban applications	1,2,3	Could utilize smaller lengths of blade; GPP; some concrete substitution	4-high
Small Housing - roofing	med	Wood, steel, roofing finish materials	Public and private; Lots of opportunity in Ireland; Middle sections could be used publicly for shelters along greenway or in parks, and privately for sheds. Holiday bungalows for 'glamping', which is very popular in Ireland. Farmers convert land into 'Glamping' holiday destinations in order to diversify. Teagasc supported.	2		4-high
Fencing & perimeter walls	med	wood, new GFRP, metal	Public and private. Highly dependent on aesthetics for private use. Might be too unwieldy for private gardens. Could be incorporated into Glamping application	3		4-high
Commodity Item: Cattle Partitions	low	Steel	Farm use. One tip would be used per head of cattle. Would require a new farm kitting or one being retrofitted.	3	Good use of offcuts or unused top tip section; steel substitution; low fabrication requirements	3-med-high
Commodity Items: Grain partition walls	low	Wood or concrete	Farm use, for partitioning grain storage areas.	3	Good use of offcuts; concrete substitution; low fabrication requirements	3-med-high
Smoking Shelter	low	steel, glass	Private; low blade utilization	2	Low utilization; Could use same design as bus or bike shelters so bundling all three applications into one product might improve utilization; steel substitution	3-med-high
Commodity Items - Planters	low	Concrete	Round planters for urban street furniture, GPP	1	GPP, Concrete replacement; low fabrication requirements	3-med-high
Bus Shelters, bike racks	low	polycarbonate, steel	Public; good public acceptance; GPP	2	GPP; medium utilization; good acceptance; steel and polycarbonate substitution	3-med-high
Commodity Items - Planters	low	Concrete	Oval planters for urban street furniture, GPP	3	GPP, Concrete replacement; low fabrication requirements	3-med-high
Commodity Items - Signage	low	steel, plastic	Bollards, verge markers or cycleway signage, GPP	3		3-med-high

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Application	Initial Design, Testing & Fabrication	Material Substitution	Feasibility in Ireland, including amount of blades utilized and GPP potential	Blade Utilized (1 = root, 2 = mid, 3 = top)	Discussion of Suitability	Overall Rank
					GPP, Good use of offcuts; steel or plastic substitution; low fabrication requirements	
Art Installation	low	anything..	Public and private	1,2,3	Low utilization, but otherwise anything is possible. Good use of scraps	3-med-high
Furniture/Street Furniture	med	wood, steel, new composite	Public and Private; medium utilization of blades. Outdoor furniture for greenways and public spaces	1,2,3	Possibility of utilizing offcuts from other projects in this application, to consume parts that might go to landfill; steel substitution	3-med-high
Noise barriers	med	Cyclefoam, recycled PVC	Public and private; high utilization along motorways;	2,3	Medium amount engineering required in order to slot blades together to seal out noise, matching aesthetics, lots of blades used. However, from geo-coastal.ie website, sound barriers are made from 'Cyclefoam' which is recycled PVC. Therefore, the material substitution rates low.	3-med-high
Quiet Pods/Outdoor Dining	low	Wood, office barriers	Public and private; restaurant use outside during winter or Covid; low blade utilization	1	Low utilization, would require larger blades for root sections to be large enough. Appealing aesthetic	2-med
Network or transmission Tower	high	Steel	Public (ESB) interest; low community interest; long testing time	1,2	Re-fabricating of transmission poles in the field might make this viable. Else transportation logistics might be a barrier; potential high utilization; GPP; steel substitution	2-med
Bio Battery	med	concrete, steel	private; farmers; low utilization	1,2,3	See 'Tank' for engineering aspect. Sections of blade could be given to farmers to create their own bio battery. Low utilization	2-med
Wind barriers urban	med	wood, metal	Public, higher acceptance in urban areas, low blade utilization	2, 3	Low utilization, could be popular aesthetically, GPP	2-med
Troughs	low	Concrete, steel, plastic	Farmers, low utilization	2,3	Include with ring and tank for farmers use; could be donated for public engagement; some steel and concrete substitution	2-med
Skate Park & Playground Equipment	med	concrete	Public, Low utilization	1	Low utilization, one off project. Legal aspects would make this difficult.	1-low
Vault	low		V44/V52 too small for this	2	Blades up through 2030 probably not big enough, and low utilization	1-Low
Bleachers	low	None – not replacing actual seats	Low interest due to base needing to be built anyway, usually wooden slats would be used on top of the concrete or the plastic bit of plastic chairs would be screwed on. Selling point is weather resistance, no maintenance and no chance of vandals ripping them up (we hope)	3	Doesn't replace actual material as bleachers are typically poured concrete	1-low
Surfboards	med	New composite	Private; likely low utilization due to needing lots of re-engineering to be useable.	3	Unlikely to be the right shape, and lots of engineering would be needed. Unlikely to be viable	1-low
Building Facade	med	Steel or timber, mid utilization	Public and private. Highly dependent on aesthetics and public acceptability, need to be clear there is no fire risk (Grenfell Tower, London)	3	Aesthetics and architectural effort would be required. This application would likely need other applications paving the way for it from aesthetics	1-low
Pile	med	Concrete, steel	Public and private; Much testing to gain acceptance, but large amounts could be used.	1,2	Would have to start with low risk applications, like piling for beach groynes. Hiding the material in the ground wouldn't inspire other reuse ideas. However, no issue with aesthetics	1-low
Impact Attenuators	med	steel, polycarbonate	Public, lots of blades utilized, unlikely due to engineering obstacles	1,2	See crash barriers. Could be used for water way barriers	1-low
Aquaduct	med	stone, concrete	Public; poor match of aesthetics in Ireland.	1,2	Poor aesthetics, low usage, lots of groundworks and engineering required	1-low
Verticalizing landfills	high	Land conservation		1,2, (3?)	Low utilization, one off project. Likely unpopular	1-low

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Application	Initial Design, Testing & Fabrication	Material Substitution	Feasibility in Ireland, including amount of blades utilized and GPP potential	Blade Utilized (1 = root, 2 = mid, 3 = top)	Discussion of Suitability	Overall Rank
			Public, low to med quantity blades utilized, engineering would be difficult			
Artificial Reefs	med	anything non-degrading material	Public	1,2,3	This would require study to ensure materials weren't hazardous submerged, in pieces. Likely unpopular due to the perception of dumping	1-low
Floating Farm	high	new GFRP?	Public and private; uncertain what the application would be in Ireland	2,3	Low utilization, unsure of application	1-low
Wind attenuators Rural	low	wood, metal	Public and private; lower acceptance rural	2,3	Likely mismatched aesthetics for rural application; could offer for farming or industrial gardener applications	1-low
Wave attenuation (beach groynes)	med	Stone, wood, concrete; low utilization	Public; likely unpopular due to poor aesthetics; low utilization	2,3	Poor aesthetics, low usage, lots of groundworks and engineering required	1-low
Pontoons	med	New composite, wood, plastic	Private; swimming platforms, boat docks; advertising platforms	2,3	Low utilization; float testing and engineering would be required. Unsure yet how well blades would float	1-low
Gateways	N/A		Include under art installation	1,2,3		0-N/A
3D printing material, aggregate, rebar for concrete, filler, fibres for clothing	Not considering at this time due to this being more in the realm of recycling than repurposing	N/A	N/A	N/A	N/A	0-N/A
Louver	N/A	N/A	skipped	3		0-low interest
Chimney Liner	N/A	N/A	Skipped, low interest			0-low interest
Crash barrier	high	steel	Public, lots of blades utilized, not possible due to engineering	2,3	Too difficult to get crash test certs	0 - impossible

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