Sustainability Assessment of the Repurposing of Wind Turbine Blades

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Declaration

I hereby certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism.

Signature

Date:

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Acknowledgements

It is fitting to be writing these final words from my dear friends Katharina and Denis's house in Cobh, as Cobh was where my thesis journey first started in February 2018. The Sirius Art Centre in Cobh was holding an art exhibition and an evening of lectures on climate change, and this was where I first came across Dr. Ger Mullally. He was speaking about the Anthropocene, the idea that we have moved into an age in which human activity has the dominant influence on climate. I was so terrified by this idea and so taken by Ger's talk, that I contacted him the next day to enquire about research opportunities on this topic. Ger replied that my timing was quite perfect, that applications for fully funded PhD positions for the Re-Wind project would be open for another two weeks. And a month later I was offered one of the PhD positions on the Re-Wind project. (It is at times like this that I think the Universe has swifter plans for us than we could have made for ourselves!)

The journey of being able to study again brought me tremendous joy… and the Re-Wind project turned out to be the perfect school bus to have stopped to pick me up! The people involved, across all the various disciplines, background and countries, offered a stimulating, but warm and encouraging environment. My supervisor Dr. Paul Leahy, was always available for insightful feedback and discussion, always encouraging, always helping me move forward. I do not know how he found the time! And through his humble approach to supervising, he gave the feeling of continuing his own learning alongside me. I also had two excellent co-supervisors from different academic disciplines. Dr. Ger Mullally was indeed one, and nudged my multi-disciplinary learning through exposure to the SDGs, social sciences and current affairs. He always communicated to me a strong belief that my research would make an impact. Dr. Niall Dunphy, my second co-supervisor, was the perfect translator between engineering, social sciences and business. Niall had a much-appreciated tendency to appear in the canteen or be immediately available at odd times when I had a particularly difficult, cross-disciplinary problem that I was trying to work out. His ability to understand and offer an excellent answer in less time than it took to make a cup of coffee showed his brilliance. I was so fortunate to get to work with Kieran Ruane from MTU for the last two years of the project. Kieran is inspirational in his enthusiasm for taking on hard projects that are simply 'the right thing to do', like the BladeBridge, and it was amazing to watch him balance the completion of this while teaching and running his own business. Dr. Russell Gentry in Georgia Tech was hugely influential during this time, both personally and academically. The confidence he displayed in me by inviting me to lead his I-Corps team, and the collaboration and work accomplished during this challenging experience were incredibly capacity building for me. I'll never forget Russell and Harriet's hospitality in Atlanta, and their kindness during my family emergency in Belfast. A big thank you to others on the project who were so excellent to work with: Emma, Chloe, Jenny, Conor, Zoe, Yulizza, Peter, Fergal, and Heloisa. Finally, a huge thank you to the project lead, Dr. Larry Bank. I so benefited from our discussions, which really kicked off at the start of Covid, and was thankful at the informal access to your time and experience. Larry's passion for the project, massive experience, and dogged efforts in organizing and promoting it meant that Re-Wind existed and was well regarded. Without Larry's effort, the project never would have taken off, and the immense gains we all experienced from working together would never have happened.

Several friends and family have played huge supporting roles the past four years. Alissa and Barty had boundless interest in my studies, and endless supportive conversations over Friday evening meals (followed by games of Marco Polo with the kids to keep things light). Katharina helped me to pull off the application in record time, and ensured me I'd be crazy not to take this funded PhD (when I said I wasn't sure I was 'really into wind energy'). Banu and Ruth offered cooking sessions, food and childcare. And Dr. Bronagh stitched my kid's heads when they injured themselves, minded me when I was sick, and offered up her home for the writing retreat in which a large chunk of this thesis was conceived.

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Finally, to my husband Roger and my beautiful and patient children Emma, Katelyn and Leo. Thank you for giving me all the time, love and support that I could ever ask for, to do what I love **second** best, outside of loving you all.

This thesis is dedicated to my step-father Dave VanAmburg, who's love of non-institutional learning was boundless!

And in memory of my older sister Danae Marie Cessna, who lived more fully in the moment than anyone else I know, and who overflowed with love and acceptance for her family, and for her baby sister.

Danae Marie Cessna
2 Feb 1971 - 24th May, 2022

Abstract

Ireland is regarded as rich in wind resources, with Wind Energy Ireland suggesting that wind generation could make Ireland a renewable superpower. Ireland has chosen to capitalise on this resource by dramatically expanding wind energy generation capacity. However, with this development of wind capacity comes the need to deal with increasing amounts of waste from the wind sector when the turbines reach end-of-life. While much of the turbine is recyclable, the blades, which are made from composite glass fibre and polymer material, is not yet economically viable to recycle. Many blades are being landfilled or incinerated at the end of their working lives. An option that is gaining in popularity is the idea of repurposing blades into useful structures.

This thesis considered the question “Can repurposing of end-of-life wind turbine blades from Irish wind turbines offer overall gains in sustainability?” Overall sustainability was by developing a Life Cycle Sustainability Assessment framework, which includes environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and the lesser established social life cycle assessment (s-LCA). LCA was used to first establish co-processing of the discarded blade material in Ireland as the most likely and best case scenario against which to compare repurposing solutions. Three overall scenarios were then developed based on maximizing blade consumption, the substitution of high embodied carbon materials, and serving customer segments who will benefit from circular material use such as the county councils who may be required to adhere to Green Public Procurement requirements. Based on these scenarios and customer segments, an estimated 20% of the blade material estimated to be decommissioned in Ireland could potentially be repurposed, offering reductions of 30,780 kg CO_2 equivalents of emissions per year. The concept of using end-of-life blades to make bridges (termed ‘BladeBridge’) was selected from the scenarios for an in depth study. LCA and LCC comparisons against a conventional bridge and the baseline disposal method, showed BladeBridge to be environmentally less impactful than both of these scenarios. From a cost perspective, the first BladeBridge using a specific blade model will be slightly more expensive than a conventional bridge and subsequent blade bridges due to the reverse engineering required to assess the residual

structural properties of the blade. However, second and subsequent bridges made from the same blade models would be less expensive. Indicators for s-LCA were developed by considering national shortfalls in Ireland's performance against the Sustainable Development Goals (SDGs), which can be considered the world's key performance indicators. In this way, these indicators capture a product's ability to affect global social indicators in which Ireland most needs to improve upon. Using LCA, LCC and the SDG based s-LCA indicators, a stage/gate screening process was developed which follows the embedded systems model of sustainability. In this framework, early business ideas can be first screened for environmental and social value, and then for cost viability. This framework can help in the development of 'purpose driven businesses.' The research presented in this thesis combined life cycle thinking with policy considerations and business value creation, and offers contributions across all of these areas. Some examples of contributions are the positioning of LCA in the repurposing debate; the creation of a framework for life cycle assessments of products made from end-of-life material that can be used to contribute to improving globally defined social and environmental metrics; analytical tools for local authorities to implement green public procurement; and support for Ireland to decouple its renewable energy generation from the production of waste.

Thesis outputs

Chapters published as papers or currently under review in peer-reviewed journals:

Chapter 4: Nagle, A.J., Delaney, E., Bank, L.C., Leahy, P.G., 2020. A Comparative Life Cycle Assessment between landfilling and Co-Processing of waste from decommissioned Irish wind turbine blades. J. Clean. Prod. 123321. https://doi.org/10.1016/j.jclepro.2020.123321

Chapter 5: Nagle, A.J., Mullally, G., Leahy, P.G., Dunphy, N.P., 2022. Life cycle assessment of the use of decommissioned wind blades in second life applications. J. Environ. Manage. 302, 113994. https://doi.org/10.1016/J.JENVMAN.2021.113994

Presentations for International Conferences

Nagle, A., 2019. An LCA Study of Incineration vs. Landfill of Wind Turbine Blades Decommissioned in Ireland [conference presentation], presented at WESC 2019, June 17-20, 2019, Cork, Ireland

Nagle, A., 2020. Sustainability Assessment of a Pedestrian Bridge made from Repurposed Wind Turbine Blades [conference presentation], in: RECOMP Nov 23-24, 2020 Conference.

A. Nagle., 2020. Sustainability Analysis of a Pedestrian Bridge made from Repurposed Wind Turbine Blades [conference presentation], presented at the 2nd Life Cycle Innovation Conference, Aug 26-28, 2020, Berlin, Germany - Virtual Event

Nagle, A., 2021. Life Cycle Assessment of the Use of Decommissioned Wind Blades in Second Life Applications, in: International Conference on Resource Sustainability [conference presentation], 19-23rd July, 2021.

Nagle, A., 2022. Sustainability Analysis of a Pedestrian Bridge made from Repurposed Wind Turbine Blades [paper presentation] in: Civil Engineering Research in Ireland, 25-26th August, 2022.

Contribution to the Papers

Chapters Published as papers or currently under review in peer-reviewed journals.

Chapter 4: I was the first author of the paper, and was responsible for research design, data collection, contacting the industry representatives, data analysis, and all LCA modelling, and the majority of the writing.

Chapter 5: I was the first author of the paper, and was responsible for Conceptualization of the blade use scenarios, methodology for assessing material substitution, data collection for life cycle inventory, LCA modelling, data analysis and the majority of the writing.

List of Acronyms

Circular Economy Action Plan	CEAP
CO_2 equivalent	CO_2 e
Construction and Demolition	C&D
Department of Environment, Climate and Communications	DECC
Disability Adjusted Life Years	DALYs
Do-it-yourself	DIY
Electric Power Research Institute	EPRI
End-of-life	EoL
Environmental Product Declaration	EPD
European Composites Industry Associate	EuCIA
Fibre Reinforced Polymer	FRP
Geographic Information Systems	GIS
Glass fibre	GF
glass fibre reinforced polymer	GFRP
Global Warming Potential	GWP
Green Public Procurement	GPP
greenhouse gas	GHG
Institution of Structural Engineers	IStructE
International Standards Organisation	ISO

Key Performance Indicators	KPIs
Life Cycle Assessment	LCA
Life Cycle Costing	LCC
Life Cycle Impact Assessment	LCIA
Life Cycle Inventory	LCI
Life Cycle Sustainability Assessment	LCSA
Life Cycle Thinking	LCT
Multi-Criteria Decision Making	MCDM
Munster Technology University	MTU
Nationally Determined Contributions	NDCs
Nomenclature of Territorial Units for Statistics	NUTS
Original Equipment Manufacturer	OEM
Potentially Disappeared Fractions	PDF·m^2 ·y
Product Environmental Footprint	PEF
Social Justice Ireland	SJI
social life cycle assessment	s-LCA
Society of Environmental Toxicology and Chemistry	SETAC
Solid Recovered Fuel	SRF
Sustainable Consumption and Production	SCP
Sustainable Development Goals	SDGs

Technology Readiness Level	TRL
tonne kilometre	tkm
United Nations Environmental Program	UNEP
United Nations Framework Convention on Climate Change	UNFCC
Voluntary National Reviews	VNRs
Waste Action Plan for a Circular Economy	WAPCE
Waste Framework Directive	WFD
Wind Energy Ireland	WEI

1 Introduction

The United Nations Framework Convention on Climate Change (UNFCCC), The Paris Agreement and the Sustainable Development Goals (SDGs) together provide the worldwide framework for addressing climate change and promoting worldwide peace and prosperity. While the UNFCCC and SDGs are suggested frameworks, the Paris Agreement, which requires a 40% reduction in EU greenhouse gas (GHG) emissions by 2030 as compared to 1990 levels, is more formally binding. To meet these requirements, Ireland plans to generate 70% of its energy through renewable sources, predominantly through wind power generation (Turner et al., 2018).

Ireland is regarded as rich in wind resources, with Wind Energy Ireland suggesting that wind generation could make Ireland a renewable superpower (Cummins, 2021). Ireland has chosen to capitalise on this resource by dramatically expanding wind energy generation capacity. Achieving 70% renewable energy will require an additional 3.5 GW of offshore and 8.2 GW of onshore wind power by 2030 (DCCAE Ireland, 2019). While the direct GHG emissions due to wind energy generation is zero and the lifecycle emissions from manufacturing, transportation, and dismantling of the turbines are 1% of non-renewable European electricity (Vestas Wind Systems A/S, 2006a), the composite blade material from the decommissioned turbines is becoming a significant waste problem (Amaechi et al., 2019; Cooperman et al., 2021; Gentry et al., 2018; Jensen and Skelton, 2018; Liu et al., 2019; Liu and Barlow, 2017). The glass fibre reinforced polymer (GFRP) thermoset composite material used is light and durable, perfect for wind blade applications, but reversing the thermosetting process in order to recycle the constituents has proven difficult. Indeed, one researcher suggested that while the tower, electronics and many other turbine components can be recycled, the blades have become the 'sustainability blind spot of wind energy systems' (Sakellariou, 2018).

While wind blades will make up only about 10% of the composite waste material in Europe by 2025 (WindEurope, 2020a), the wind energy sector must find a solution to its waste in order to uphold its promise of being a 'sustainable' option. The composites industry has been aware of the difficulties of post-use recovery in thermoset materials for over 25 years (Henshaw et al., 1996), but without policy specifying end-of-life disposal requirements, there has been little incentive to redesign the material until recently. Years of efforts have been made to develop recycling technologies for thermoset material, but few are financially viable (WindEurope, 2020a). Repurposing of the material is higher on the waste hierarchy, but until recently, has been dismissed as incapable of dealing with the expected volumes of material. However, this dismissal of a potentially innovative partial solution may be premature. Repurposing of renewable energy 'waste' may in fact offer benefits both within and beyond this sector.

In the public's mind, wind turbines have become a ubiquitous symbol for the global move towards sustainability. While blade waste may not be one of the larger scale problems within the construction industry, the publicity of this previously unknown issue could serve to show that even the most conspicuous sustainable technology can have "hidden" problems. The absence of full life cycle considerations in the original design of wind blades can be used to educate on why life-cycle thinking is important. The symbolic nature of the "green" wind turbine can be exploited and its end-of-life problem can show why a whole-life-cycle approach is now necessary. Repurposing of blades in very visible civic settings can vividly convey the importance of considering the full life-cycle of any sustainable solution and help foment new ideas around end-of-life product decisions. The blade waste issue could become a breakthrough example of the importance of life-cycle thinking.

1.1 Statement of Purpose and Research Questions

This thesis will explore the sustainability aspects of repurposing discarded Irish wind blade material by considering regional life cycle thinking, current policy and the United Nations Sustainable Development Goals. Several research questions are addressed in order to explore this idea of repurposing blade material into useful structures. The first question is around determining how blade material is currently being handled at end-of-life, to create an environmental benchmark against which we can measure new proposed solutions.

Q1: Currently, what are the most likely end-of-life disposal methods for Irish wind turbine blade material, and what are the environmental impacts of these methods?

This question is addressed in chapters two and four.

The second question begins to consider multi-criteria decision making to look at environmental and policy implications of optimizing blade material use in Ireland.

Q2: What blade repurposing scenarios offer the most environmental gains considering the options most likely to be implemented in Ireland based on business demand and policy?

This question is addressed in chapter five.

The third question examines the use of the Sustainable Development Goals in business practices, and in selecting regional social life cycle assessment (s-LCA) indicators.

Q3: How could social life cycle assessment criteria be developed for assessing new business models in Ireland, considering both national and planetary needs?

Chapter seven addresses this question.

The fourth question combines learnings from the previous studies, to assess the sustainability of an as-built project in Ireland.

Q4: How would a pedestrian bridge built using discarded wind blades offer life cycle cost, social and environmental improvements?

Chapters six and eight explore this question.

The concluding chapter aims to answer the following overarching thesis question:

Can repurposing of discarded Irish blade material offer overall gains in sustainability?

Answering these questions relies on a multi-, inter- and trans-disciplinary approach to the research, the necessity of which is discussed in chapter two. This approach was enabled by working within The Re-Wind Network, a project that was purpose-built to foster inter- and trans-disciplinary innovation. The details of this project will be discussed in chapters two and three.

1.2 Structure of Thesis and Research Contributions

This thesis contains nine chapters. The first chapter is the Introduction, which outlines the research questions and the motivation behind the work. Chapter two is a literature review which offers a more detailed context in which the research is conducted. Chapter three describes the overarching methodology used within the thesis. It details the Life Cycle thinking framework used in the quantitative research, including Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), and the lesser- established Social Life Cycle Assessment (s-LCA) and Life Cycle Sustainability Assessment (LCSA). Chapter three also describes the disciplinary structure within which this thesis is conducted, and how the iterative collaboration enriched this research.

Chapter four is the first of four quantitative studies within the thesis. This chapter uses LCA to establish an environmental baseline of currently used blade disposal options. It compares the options of landfilling of material against transporting the material abroad for processing. These results are used later in the thesis, against which newly developed repurposing scenarios are compared. This study is the first full LCA comparing end-of-life options for blade waste, and contributed to the Wind Europe discussion in support of a European landfill ban.

Chapter five develops three theoretical repurposing scenarios for Irish blade material. The scenarios are designed based on maximizing the utilization of blade material, environmental improvements due to material substitution as measured using LCA, and the likelihood of adoption based on EU and Irish policy. The research contribution was to quantify potential environmental gains through realistic repurposing scenarios in Ireland. A second contribution was the development of an estimated amount of CO_2 emissions reductions per tonne of blade material repurposed. These calculations could contribute to the uptake of blade products by customers who are publicly accountable for their CO_2 emissions.

Chapter six is a study of a pedestrian bridge made with decommissioned blade material, built in Ireland during the course of this research. A comparative LCA and LCC are conducted to identify environmental and cost hot-spots throughout the bridge life cycle, as compared to a conventional bridge. From a waste management perspective, an LCA and LCC are also conducted to compare the use of blade material in a bridge as compared to the baseline disposal method established in Chapter 4. This chapter is the first known LCA and LCC of a product made with repurposed wind blades, and demonstrates that the repurposing of blade material in infrastructure projects can offer environmental improvements at a similar cost to the use of conventional material.

Chapter seven gives a brief history of the Sustainable Development Goals, and suggests a method for using national shortfalls in performance against the SDG to develop indicators for s-LCA. These Irish specific s-LCA indicators can feed into a LCSA framework which is better designed to assess local products for their contribution to both Irish and global needs. This method of s-LCA indicator development can be replicated for other projects in other regions, and can contribute to forming an overall methodology for early-stage planning of 'purpose driven' products and businesses.

Chapter eight is a Life Cycle Sustainability Assessment of the pedestrian BladeBridge. The LCSA utilises the s-LCA indicators established in Chapter seven, as well as the LCA and LCC results from chapter six. The main research contribution is a novel approach to LCSA which combines the embedded systems model of sustainability with a linear stage-gate approach to performing the LCA, s-LCA and LCC frameworks. This assessment can feed directly into the formation of a blade repurposing business that offers blade products that are more sustainable across their life cycle than conventional products, as supported by research.

The ninth and final chapter concludes with a discussion on the potential for repurposing of blade material to generate overall gains in sustainability, and also covers future plans for scaling up implementation of this research.

While the topics of LCA and LCSA, wind turbine blade end-of-life options, repurposing of construction waste, and the SDGs have been covered extensively in the literature, the combined application of LCSA and the SDGs to the topic of wind turbine blade repurposing has not yet been conducted. This thesis applies the framework of LCA and LCC to the novel application of the comparison of end-of-life options for wind blade material, both from a waste diversion as well as a repurposing and material substitution perspective. The use of the SDGs to create regionally specific s-LCA indicators, which are then incorporated into an LCSA framework, is a novel methodology. Finally, the use of this LCSA methodology to assess the second only in the world pedestrian bridge built from decommissioning wind turbine blades, is entirely novel in both methodology and application. Although this study was conducted on blade material decommissioned and repurposed in Ireland, the methodology and application are very transferable both to other geographical areas, as well as in other repurposing projects.

1.3 Conclusion

This chapter introduced the problem of end-of-life wind turbine blades in the renewable energy sector in Ireland, and has suggested that repurposing of the blade material is a valid end-of-life solution. Life cycle thinking and the Sustainable Development Goals were introduced as two frameworks which factor heavily in this thesis. The research questions were described according to the chapter in which they are addressed, and the structure of the thesis and research contributions were presented.

The next chapter is a literature review which offers a more detailed context in which the research is conducted. This chapter estimates the expected blade waste problem in Ireland, and positions 'repurposing of blade material' as a valid end-of-life option. Life cycle thinking is introduced as a framework for assessment of end-of-life options, and an argument is established for engaging in transdisciplinary teamwork to enrich the research.

2 Literature Review

2.1 Blade Waste Quantification in Ireland

Wind turbine blades are made predominantly from glass fibre reinforced polymer (GFRP), a composite material formed by the use of glass fibre reinforcement strands, with a thermoset polymer matrix such as epoxy. GFRP material has a high strength to weight ratio and is resistant to fatigue, corrosion, and electrical and thermal conductivity (Jensen and Skelton, 2018; Mishnaevsky et al., 2017). These properties, combined with the low cost of materials, make the construction of lightweight, durable and cost-effective wind turbine blades possible. The drawback of a thermoset polymer matrix is that the curing process is irreversible, making recycling efforts difficult and costly (Jensen and Skelton, 2018). More details on the structure of the blade and additional material layers are discussed in chapter four.

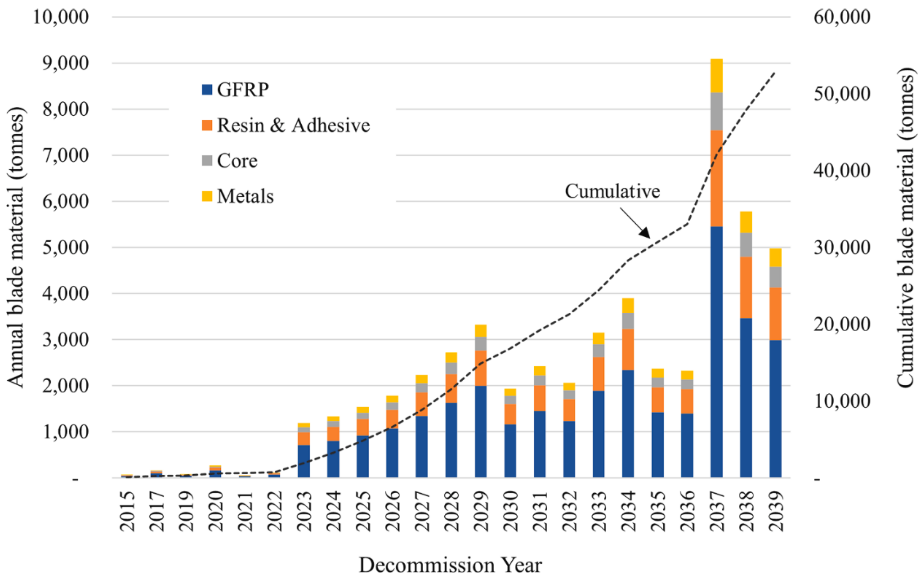

Figure 2.1 Estimated cumulative and annual blade material quantities for onshore wind farms in Ireland (Delaney et al., 2021)

Wind turbines have an expected service life of 16 – 25 years (Jensen et al., 2020; Sommer and Walther, 2021). Irish blade amounts estimated using a 20 year lifespan show a cumulative 53,000 tonnes of GFRP material generated on the island of Ireland by 2040, peaking at over 9,000 tonnes per year at 2037 (Figure 2.1) (Delaney et al., 2021).

In Ireland, only small numbers of individual turbines or damaged blades have been discarded to date. Companies including WindTranz, Everun and Veolia have been involved in the decommissioning process, and thus far, blades have been landfilled, or stored temporarily in the hopes that a more circular or more economical disposal solution will emerge. Wind Energy Ireland (WEI) estimate that it will be 2023 or later before entire wind farms will be decommissioned in Ireland, at which time larger quantities of GFRP material will need to be handled (J. Moran, Wind Energy Ireland, personal communication, 19th February, 2021).

2.2 Blade Waste 'Disposition' Options

The end-of-life disposal options for blades are discussed extensively in chapter four, and thus, only a high-level description supplemented by applicable new research is presented in this section. The Waste Framework Directive (WFD) (European Commission, 2008a), which first introduced the waste hierarchy, is used to structure this review of end-of-life options. Figure 2.2 depicts the hierarchy from the perspective of composite material end-of-life options. The discussion will start from the top of the pyramid with the most favourable options included in 'Prevention', and work down to the least favourable options included in 'Disposal'.

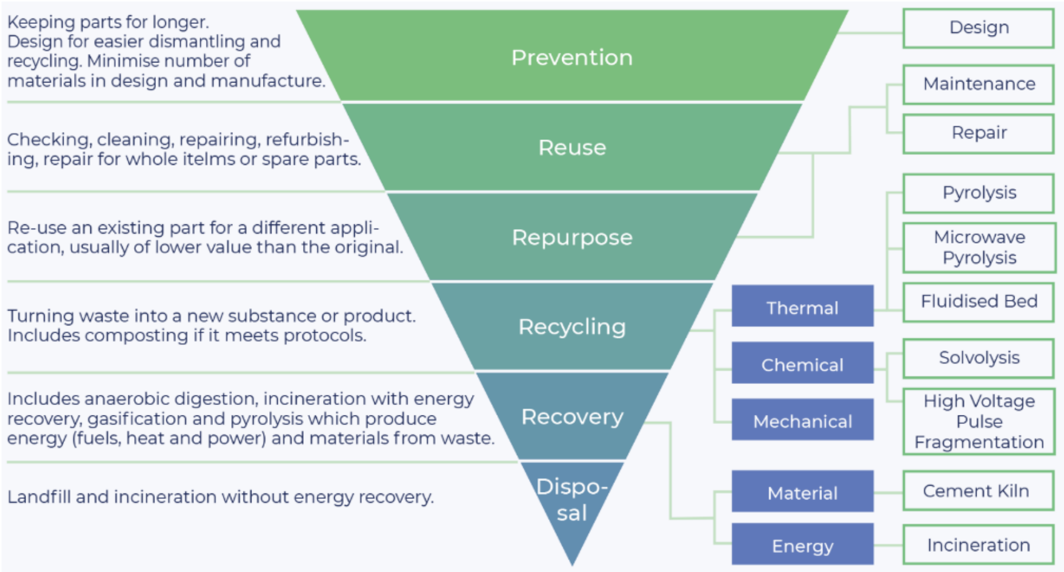

Figure 2.2 European Waste Hierarchy for composite material end-of-life (Ierides et al., 2018)

'Prevention' of waste includes lifetime extension of a product. From an overall standpoint of the lifetime environmental impact of blade material, extending the lifetime of the blade is clearly the best choice (Mishnaevsky, 2021). A study of Vestas onshore V112-3.45 MW turbines calculated lifetime global warming potential (GWP) as dropping from 6.6 g CO_2-e per kWh at 16 years to 4.4 g CO_2-e per kW at 24 years (Razdan and Garrett, 2017). Another life cycle assessment of a 3.2 MW onshore wind turbine showed the GWP dropped from 8.7 kg CO_2/MWh for 10 years lifetime to 2.8 kg CO_2/MWh for 30 years (Pagh, 2018).

'Reuse' includes repairing or refurbishing blades for use as spare parts or for re-sale. Full turbines or individual blades are often sold on the second hand market (Sakellariou, 2018). Reuse is more likely, however, when a turbine is decommissioned before reaching the end of its design life because the blades have seen less wear, and less likely after lifetime extension beyond the design life of 20 years (Pagh, 2018).

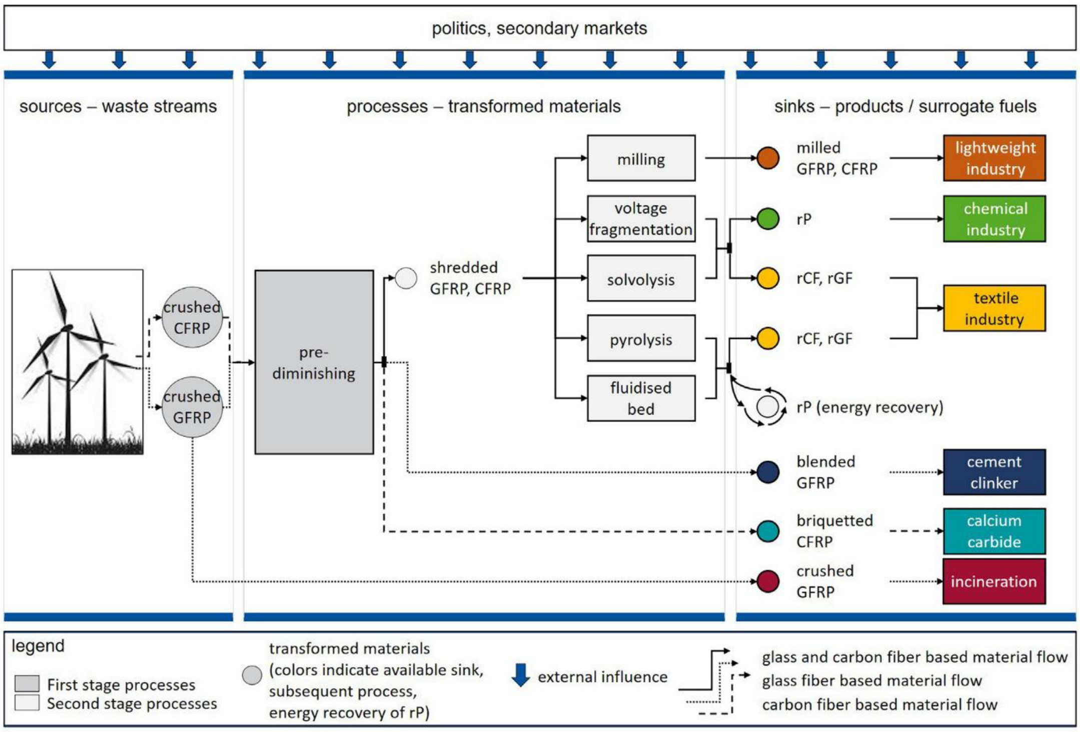

Figure 2.3 Source, processes, and sinks for blade recycling options (Sommer and Walther, 2021)

'Repurposing' keeps the structural and material properties of the composite intact, by utilizing all or smaller sections of the blade for new purposes (Gentry et al., 2020). Examples include roofing for temporary housing (Bank et al., 2018a), pedestrian bridges (Speksnijder, 2018; Suhail et al., 2019), transmission towers (Alshannaq et al., 2021a), bike shelters (WindEurope, 2020a), furniture (Adamcio, 2019), and other items such as sound barriers and 'glamping pods' (McDonald et al., 2021). Repurposing the material into a second life use has the benefit of the material being available for a third or fourth life use in the future, further utilizing the properties of the material (Joustra et al., 2020).

'Recycling' is the process of breaking down the GFRP material into constituents that can then be used. Blade material recycling options are categorised as thermal, chemical, or mechanical as is shown in the composite waste hierarchy in Figure 2.2 (Ierides et al., 2018). A more recent study categorised these options according to the quality of the transformed material and the potential end use or 'sinks' for the recyclate (Figure 2.3). The study also included assessments of the circularity of each process, benchmarked against potential ‘recycling quotas’ that could be introduced in Europe (Sommer and Walther, 2021).

Milled, or mechanically ground GFRP material can be used in lightweight industrial applications such as construction panel board (Global Fiberglass Solutions, 2021) or cable troughs (Reprocover, 2021). The milling process has an estimated yield of 55%, making it recyclable but not very circular, but does have the potential for positive revenue. Voltage fragmentation and solvolysis generate a polymer portion that may be utilized by the chemical industry, but the recycled glass fibre (GF) quality is too low to be reused. These processes have a technology readiness level (TRL) of 5/6 (WindEurope, 2020a) due to their low processing capacity and high cost. Pyrolysis and fluidized bed process also have a TRL of 5/6 (WindEurope, 2020a), and allow recovery of the GF portion for the textile industry, while utilizing the polymer portion through energy recovery. Use of the recycled GF in the textile industry has the potential to meet recycling and circularity targets (Sommer and Walther, 2021).

‘Recovery’ includes incineration and processing in a cement kiln. 1000 kg of blade material can replace 600 kg of coal as energy generation in both processes (Liu et al., 2019). Additionally, the use of blade material in the cement kiln can substitute an amount of raw clinker material (Hanes et al., 2021; Nagle et al., 2020). However, it is expected that the amount of blade waste generated in Europe per year will exceed the cement kiln capacity by 2025 (Wind Europe, 2021a), and that this option will become less popular if recycling or circularity quotas come into effect (Sommer and Walther, 2021).

‘Disposal’ includes landfill and incineration without energy recovery. Landfilling of blade material has been banned in Austria, Finland, Germany, France and the Netherlands (Wind Europe, 2021a), while the wind energy industry group Wind Europe have called for a European wide landfill ban by 2025 (Wind Europe, 2021b). Incineration without energy recovery reduces the waste volume by approximately 40%, but the remainder of material still requires landfill (Jensen and Skelton, 2018).

Overall, there is not a clear path to dealing with large quantities of GFRP blade waste. Wind farm owners may choose lifetime extension for their wind assets, after which the value of the blades on the second-hand market is reduced due to their advanced age. Ultimately, however, the blade material will reach end-of-life and the choice of what to do next with the material must be made.

Repurposing is next highest on the waste hierarchy, but has been regarded by Wind Europe as 'mainly demonstration projects' that do not represent a large-scale solution for European blade waste quantities (WindEurope, 2020a). Recycling is next, however, many studies show that the cost of chemical or thermal recycling of GFRP is still too high while the quality of the GF is too low (Ginder and Ozcan, 2019). The favoured end-of-life options are either mechanical recycling (Liu et al., 2019), or, despite being lower on the waste hierarchy, recovery in a cement kiln (Sommer and Walther, 2021). However, market demand has not been established for products made from mechanically recycled GFRP, while European capacity for processing in a cement kiln will be exceeded mid-century. None of the existing End-of-life options for GFRP waste, on their own, is a clear winner. However, a combination of these approaches, whereby the material is conserved as close to its original form as possible through repair and lifetime extension, repurposing or storage, until larger scale recycling technologies have been developed, may be the way forward.

2.2.1 Defining *To disposition*

In many industries including engineering and construction projects, semi-conductor and pharmaceutical manufacturing, and software development, this process of 'choosing what to do next with a product or material that was removed from operations' is referred to by the verb *to disposition*. This term disposition will be used widely in this thesis to refer to the end-of-life decision that is made for decommissioned blade material. The choice of landfilling, incineration, recycling, repurposing, reuse and lifetime extension are all potential 'dispositions' for blade material.

2.2.2 Stockpiling

Temporary storage, or 'stockpiling' of blade material is an interim end-of-life disposition that is being used. Stockpiling is simply the *'accumulation of a large stock of goods or materials'*. However, it tends to have a negative connotation, as when imagining countries 'stockpiling' weapons, or early in the Covid-19 pandemic when neighbours were thought to be 'stockpiling' food or toilet paper. Storage of waste material is allowed, according to the WFD Article 3(15) in the case of (among other things) ‘Recovery’, which is defined as ‘… waste being prepared to fulfil the function of…replacing other materials…in the wider economy,’ with Annex II(R5) listing recovery options as ‘Recycling/reclamation of inorganic materials’ (which includes recycling of inorganic construction materials) (European Commission, 2008a). A European case study of recycling and recovery infrastructure for GFRP and Carbon FRP waste from the wind industry argues that any modelling of recycling and recovery infrastructure should allow for temporary storage options for blade waste (Sommer and Walther, 2021).

Based on the WFD, the EPA defines waste as ‘Any substance or object which the holder discards or intends or is required to discard’. The holder’s intention, therefore is key to the classification, and an intervention must be made at the time of decommissioning to avoid blades entering the waste regime. Therefore, the owner must be made aware of the intention to ‘recover’ the material, and must allow the handling of the material through non-waste transport. At this point, blades can be aggregated for an intended ‘recovery’ process which will ‘replace the use of primary raw materials’ for an extended amount of time. Stockpiling an allowed number of blades would offer a reliable, pre-inspected material supply which could help overcome barriers to repurposing.

2.3 Repurposing of Wind Turbine Blades

Once the life of a blade cannot be further extended and has no value as a spare part or on the second hand market, repurposing is the next most environmentally beneficial option (Velenturf et al., 2021). When blade material is substituted for raw material that would have been used, repurposing clearly represents the best option when reuse and lifetime extension are no longer an option. Blades are highly engineered components designed to take 20 years of repeated cyclical loading. GFRP material has a high strength to weight ratio, and, as mentioned earlier, is resistant to fatigue, corrosion, electrical and thermal conductivity (Jensen and Skelton, 2018), properties which are extremely desirable in civic infrastructure applications as well as wind turbine blades. Choosing to build a product using new GFRP material rather than a conventional material such as metal, would typically cost more (Ilg et al., 2016). The excellent mechanical properties and high cost of new GFRP have not so far resulted in the exploitation of the value of GFRP material at the end of the blade service life. Instead, companies pay over €200/tonne to dispose of them (Laois County Council, 2021).

2.3.1 Main Barriers to repurposing blades

Some of the barriers to repurposing blades are the same as repurposing construction and demolition (C&D) waste, such as a lack of standards for the assessment of used or reclaimed material, and consumer perception (Shooshtarian et al., 2020). However, blade repurposing presents other challenges. The geometry is quite complex, with few flat or linear sections to work with which makes designing for large sections of the blade difficult (Gentry et al., 2020). The blade manufacturers are unwilling to release details of the GFRP layup or the internal geometry of the blade, and therefore reverse engineering is required to determine the structural properties (Ruane et al., 2022). Finally, the aesthetics could prove challenging, particularly in communities in which wind energy is not popular (Kwon et al., 2019).

2.3.2 Large Scale and Civic Structures

SuperUse Studios have constructed the greatest number of large structures using discarded blades, with six such projects across The Netherlands (SuperuseStudios, 2021). Removable urban furniture was constructed in 2012 in the town of Rotterdam using nine small wind blades (Figure 2.4). The furniture was repainted in 2020, to develop a monument where the LGBTQI+ community can meet respectfully and safely (Superuse Studios, 2020).

Figure 2.4 The Willemsplein, Netherland urban blade furniture (Superuse Studios, 2020)

The Polish waste company Anmet has recently installed a pedestrian bridge in the town of Szprotawa, using two wind blades bolted together at the root sections as the single central support girder (Figure 2.5) (Adamcio, 2019).

Figure 2.5 Anmet pedestrian bridge in the town of Szprotawa (Stone, 2022)

The Port of Aalborg installed a bike shed early 2020 made from a blade donated by Siemens Gamesa (Figure 2.6), which is the largest company in Aalborg and located right next to the port. The middle section of the blade was left as waste, after the root section had been removed for testing. The shed was conceptualized and designed by a civil engineer working for the port environment and construction sector (Eilers, 2020).

Figure 2.6 Bike Shed in the Port of Aalborg, from a Siemens Gamesa blade section (photo credit: Henrick Eilers)

Two other bridges have been designed but not yet built. The first, Stijn Speksnijder 2018 Master's Thesis at Delft University (Speksnijder, 2018), uses two blades as the superstructure, oriented in the flap-wise direction (Figure 2.7). The bridge is intended for lightweight traffic.

Figure 2.7 Concept bridge design for Speksnijder's Masters Thesis (Speksnijder, 2018)

The second design was a collaboration between Siemens Gamesa and SuperUse Studios, for a 25m pedestrian bridge in Aalborg. The blades are also oriented in the flap-wise direction, but serve as the decking as well as the superstructure (Figure 2.8) (André et al., 2020).

Figure 2.8 Concept bridge design for a 25m pedestrian bridge (André et al., 2020)

2.3.3 Smaller or Commodity Efforts

Smaller items such as furniture and outdoor planters have also been built. As part of the Ecobulk project , a flat-pack construction style picnic table was made as a demonstration project using cut pieces from the top section of a blade (Figure 2.9a and 2.9b) (Joustra et al., 2020). This effort intended to show the potential of segmenting blades into construction elements that could be used in a wide range of commodity items such as decking, tables or cabinets.

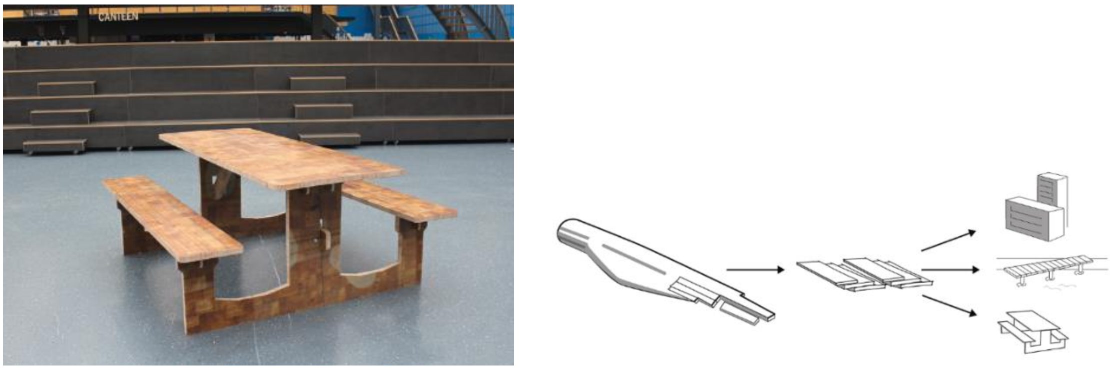

Figure 2.9a Picnic table, made from construction elements cuts from a wind turbine blade (Joustra et al., 2020). Figure 2.9b: Other commodity items that could be made from blade segments.

A range of outdoor furniture designed and built by Anmet is available for sale (Adamcio, 2019). Sun loungers, flowerbeds, and benches are made combining sections of the blade with natural material such as wood (Figure 2.10).

Figure 2.10: Park bench constructed by Anmet in Poland (Adamcio, 2019)

2.3.4 Re-Wind Project Repurposing Efforts

The research in this thesis was conducted as part of the Re-Wind project, which aims to compare sustainable End-of-life repurposing options for wind turbine blades using data driven structural modelling, Geographic Information Systems, and life cycle sustainability assessment (Bank et al., 2018c). The team is made up of researchers from a variety of disciplines, which include structural and civil engineers, architects, geographers, sociologists, and environmental engineers, across universities in Northern Ireland, the United States, and Ireland. The team generated an open source design catalogue in 2018 which included 47 concepts for blade reuse, ranging from noise barriers to stadium seating, slurry tanks to cell towers, and roofing to skate parks (Figure 2.11) (Bank et al., 2018b).

Figure 2.11 Repurposing design concepts, as presented in the Re-Wind design atlas (Bank et al., 2018b)

Figure 2.12 Re-Wind 'BladePole' transmission line design concept (McDonald et al., 2021)

Figure 2.13 Re-Wind BladeBridge design concept with blades extending beyond the bridge deck (McDonald et al., 2021)

Several of the large-scale civic concepts were then chosen for further development in specific regions. In Ireland where cycleway development is being heavily funded, the pedestrian bridge concept was chosen for prototyping (Figure 2.13). In the United

States, where the transport of longer blades is more possible logistically, the transmission tower concept was selected (Figure 2.12) (Alshannaq et al., 2021b).

Figure 2.14 Re-Wind design concept for a bus shelter (McDonald et al., 2021)

Smaller-scale concepts were next selected for further exploration, also based on regional issues. In Ireland, bus shelters (Figure 2.14) and farming equipment (Figure 2.15) were chosen for further modelling, based on new requirements for sustainable public spending (DECC, 2021) and the large agricultural sector in Ireland. In the States, noise and construction barriers were further developed, based on the research team's location in urban Atlanta. A second open sourced catalogue containing more detailed modelling was released in October 2021 (McDonald et al., 2021).

Figure 2.15 Re-Wind cattle feeding trough design concept (McDonald et al., 2021)

Cross-disciplinary, multinational collaboration was built into the design of the Re-Wind group. Chapter three will detail how this collaboration was done, and how it contributed to the high-level methodology of this research. The next section of this chapter describes the importance of expanding the capacity of engineers as well as other researchers, to move from disciplinary, to multi-disciplinary and inter-disciplinary, to finally engaging in transdisciplinary work, which in turn could help to solve some of the world's most difficult problems.

2.4 Importance of Transdisciplinary Work in Problem Solving

Meeting the climate change requirements in the Paris Agreement, without shifting environmental burdens elsewhere and while promoting peace and prosperity, is no small task. Engineers have a responsibility to help correct the damage that has been caused by poorly designed, unsustainable technology (Vanasupa et al., 2010). At the core of the engineering profession is to 'make the best use of the Earth's precious wealth', 'to work for the public good' (Order of the Engineer, 2022), and to 'protect the public interest' (Association of Consulting Engineers of Ireland, 2017). In her 2010 article correlating mental models and sustainable design, Vanasupa asks, '*Why are we as engineers currently and collectively engaged in unsustainable design?'* The answer to this question must lie in the inability of engineers and designers to understand the full consequences of their technology. Developing a working understanding of the long term environmental and social impacts of a design will require a more complex level of knowledge than has ever been required of an engineer. Vanasupa further posits that surely this damage is an unintended consequence of the current process, and that for further improvement, this profession may have to undergo a paradigmatic shift by challenging our current mental models (Vanasupa et al., 2010).

Mental models give us a lens through which to view the world, and are shaped throughout our lifetimes by our experiences, gender, nationality, friends and family, and the information we consume. Our education and professions shape our mental models as well, and depending on the approach an institution chooses to follow, can unfortunately lead to colleagues with similar mental models working together for lengths of time.

Multidisciplinary and interdisciplinary collaboration with others with different mental models should be welcomed in climate change research where genuine innovation is urgently needed. Cross-disciplinary collaboration can take many modes, and can be described in somewhat of a progression from separate, to quite integrated, to transcending disciplines.

Multidisciplinary research involves researchers from different backgrounds, at some point in time, working on the same project or problem. They bring their own set of skills and perspectives to the work, and may formulate and address separate research questions, while coming up with separate conclusions. This approach undoubtedly contributes more to the overall knowledge base than a single disciplinary approach, however it likely misses interactions between different areas of influence (Gehlert et al., 2010).

Interdisciplinary research allows for the transfer of knowledge from one discipline to another (Nicolescu, 1997) or the combination of knowledge from multiple specialties (Brewer, 2012). Collaborators share their methodology and findings, and new disciplines can emerge from this type of work, such as 'Health Economics' (Gehlert et al., 2010). Time must be spent on ensuring that collaborators understand each other's terminologies and methodological approaches. However, researchers still have separate goals or questions that they are working to answer, and may find there is little incentive to continue engagement with the work once their own goal is achieved.

Transdisciplinary research is the study of everything in between the disciplines, with a focus on understanding the world in all of its complexity, and a recognition of the unity of knowledge (Nicolescu, 1997). It requires all researchers to work towards answering the same research question. Transdisciplinary research entails the group to pool their best theories, create a new lexicon, and develop a shared methodology with which to approach the research (Gehlert et al., 2010). New mental models can develop through this work. Transdisciplinary research is challenging to achieve, however, as it entails researchers to operate outside their comfort zone and to spend extra time on learning new approaches, neither of which is necessarily rewarded in the current academic set-up (Gehlert et al., 2010). Even the act of finding researchers interested in participating in transdisciplinary research can be difficult. However, Nicolescu (1997) argues that a transdisciplinary evolution in education is crucial, stating that '*The emergence of a new culture, capable of contributing to the elimination of the tensions menacing life on our planet, will be impossible without a new type of education, which takes into account all the dimensions of the human being.*' Creating projects that offer rewarded opportunity for transdisciplinary research will begin to shift and create new mental models, which will contribute to the educational changes required to develop breakthrough technologies.

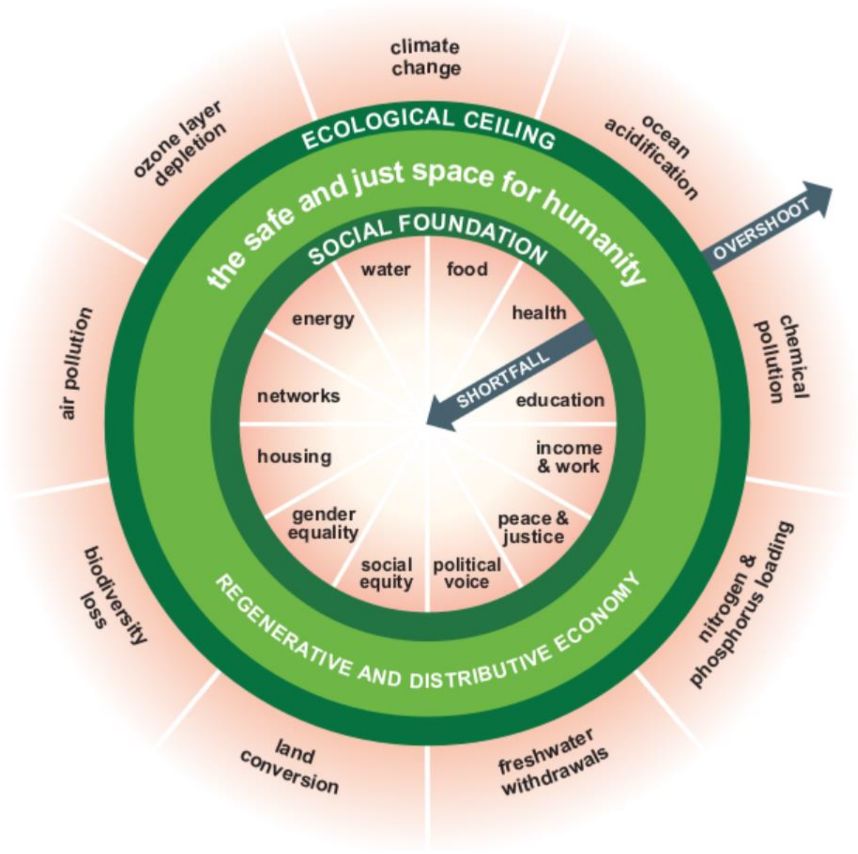

Figure 2.16 Doughnut Economics Model, as developed by Kate Raworth (Raworth, 2017)

In addition to shifting mental models, there are calls to replace several physical diagrams that are commonly used, in order to assist this change. Kate Raworth suggests the ‘Doughnut’ model (Raworth, 2017) as a replacement to several popular economic models, to promote a more sustainable approach to economic thinking and design (Figure 2.16). The doughnut represents the boundaries that we must stay within, for all aspects of our profession and lives (Raworth, 2017). The inner circle represents the social foundation, inside of which there is a lack of essential provisions for well-being. The outer circle represents the planetary boundaries, beyond which indicates a contribution to environmental degradation. Although Doughnut Economics does not specifically link to the Sustainable Development Goals (SDGs) or environmental Life Cycle Assessment (LCA), the SDGs could easily be used to measure social issues (inner), and LCA could be used to measure environmental degradation (outer). Thus, for this thesis, the Doughnut Model has greatly assisted in visualising the interaction between LCA and the SDGs. LCA will be discussed later in this chapter, and extensively in chapter three. The SDGs are discussed in detail in chapter seven.

A second recognizable model is the 'Overlapping Systems Model' of sustainability, with the three circles each representing the economy, the environment and society, and the overlap between them indicating where a sustainable approach lies (top of Figure 2.17). However, this model promotes the idea that the economy, the environment and society all have separate and competing goals, and ignores the fact that economic activity happens only within a society, which exists only within the environment.

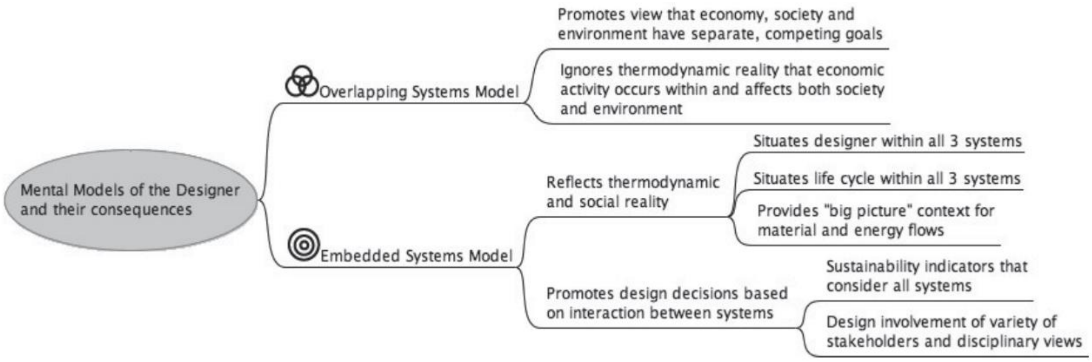

Figure 2.17 The mental models of sustainabiliy: the Overlapping Systems Model v. Embedded Systems Model, and their consequences (Vanasupa et al., 2010)

A model which better reflects these interactions might be the Embedded Systems Model. This model promotes design through the use of sustainability indicators across all three fronts, reflecting the economy's embedded dependence on society, which is depended on the environment. (Figure 2.17 and Figure 2.18).

Figure 2.18 The Embedded Systems Model of sustainability, recreated from (Daly, 1990; Vanasupa et al., 2010).

The methodology used to build cross-disciplinary approaches within the Re-Wind team will be further described in the Methodology section, chapter four. The remainder of this chapter will explore existing research in the author's main area of contribution to the Re-Wind project: Life Cycle Thinking. Understanding Life Cycle Thinking can be enhanced by starting with the embedded systems model of reality, while also considering the doughnut economics model.

2.5 Life Cycle Thinking and Circular Economy

Life cycle thinking (LCT) is an approach which considers the burdens throughout the lifecycle of a product, service, project or sector, from raw material extraction through end-of-life (Sala et al., 2021). Life Cycle Assessment (LCA) is the framework typically used to perform a quantitative assessment of a life cycle. Developed over 30 years ago, LCA aims to measure environmental impacts across all stages of a life cycle, and across a specified time (ISO, 2006a). This holistic approach to the accounting of environmental impacts helps to avoid shifting burdens between impact categories (e.g., reducing climate change while increasing air or water pollution), regions (e.g., reducing local impacts while shifting the burdens to another country), and life cycle stages (e.g., decreasing impacts during the use phase, while increasing end-of-life impacts) (Sala, 2019). LCAs until recently have been performed by specialist consultants trained to use the LCA software and ISO framework (ISO, 2006a). However, with increased awareness of the importance of life cycle thinking, LCA capacity is being incorporated into businesses' skillsets, and, importantly, is starting to be used at the design stage in many industries. Life cycle thinking includes the consideration of life cycle costs (LCC) and social life cycle impacts as well. Although not as fully developed as LCA and LCC, social LCA (s-LCA) uses a similar framework to assess social impacts or improvements across the lifecycle of a product or process (Benoît Norris et al., 2020). The following section will give a brief history of LCT in EU policy that is relevant to this research.

2.5.1 A Brief History of Life Cycle Thinking

LCT has become pivotal in integrating sustainability into policy making (Sonnemann et al., 2018), and has been increasing in use in policies since the 1990's (see Fig. 2.19), starting with the introduction of the Ecolabel Regulation in 1992 (CEC, 2009) which established a voluntary award scheme to promote products with reduced environmental impacts, as measured using LCA (Sala et al., 2021). Many EU countries developed their own ecolabels, such as the Nordic Ecolabel and the German Blaue Engel, and several more countries launched national product strategies with LCA as the core methodology (Hauschild et al., 2019). In 2008 the WFD was released (Fig. 2.2) which established a hierarchy to help in waste management decisions. The WFD requires 'handl(ing) of waste in a way that does not have a negative impact on the environment or human health' (European Commission, 2008a), which requires the use of LCT, and benefits from LCA to make quantitatively informed decisions (Hauschild et al., 2019).

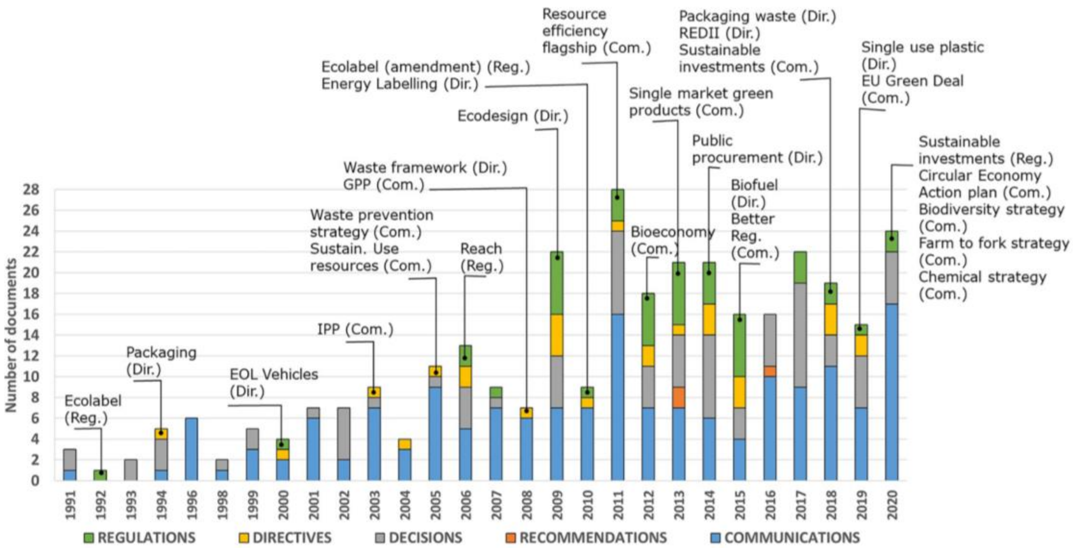

Figure 2.19 Policy development in Europe involving Life Cycle Thinking (Sala et al., 2021)

Also released in 2008 was the Sustainable Consumption and Production (SCP) and Sustainable Industrial Policy Action Plan (SIPA), the core principle of which is 'to improve the energy and environmental performance of products and foster their uptake by consumers' (CEC, 2008). One of the core principles in SCP is Sustainable Public Procurement. In 2014, the 2004 Public Procurement directive was revised to *'increase the efficiency of public spending…to enable procurers to make better use of public procurement in support of common societal goals… for smart, sustainable and inclusive growth in their purchasing strategies.'* (CEC, 2014). LCC when used in conjunction with LCA, which will be further discussed in chapter six, is called environmental LCC. E-LCC can assist in the implementation of Sustainable, or Green Public Procurement (GPP) by identifying environmental and cost 'hot spots' in the lifecycle of a product (Hauschild et al., 2019). Comparisons can be drawn between suppliers and products that have historically been used, versus suppliers and products that are claiming to be more 'green', to assist local governments in making data driven procurement decisions to reduce environmental impacts.

2015 saw two important international policy developments that required the utilization of LCA: The 2030 Agenda for Sustainable Development Goals (SDGs) and the Paris Agreement. The SDGs are 17 interlinked goals designed to be a 'blueprint to achieve a better and more sustainable future for all' (UN General Assembly, 2015). While not legally binding, the United Nations encourages each member state to conduct Voluntary National Reviews (VNR) of its progress against the goals. Ireland has committed to conducting a VNR every four years, with its first in 2018 (Oireachtas, 2018). The Paris Agreement, however, is more formally binding and was adopted by nearly every nation. Its aim is to limit global temperature rise by reducing greenhouse gas emissions, providing a framework for transparent and reliable carbon accounting, and mobilize support for climate change mitigation and adaptation for developing nations. The accounting is done through Nationally Determined Contributions (NDCs), based on each country's commitment and capacity for curbing emissions (UNFCCC, 2015). LCA is an important tool for both of these policies. It is used to measure progress against sub-goals within SDGs 11 (Sustainable Cities and Communities), 12 (Responsible Consumption), 13 (Climate Action), 14 (Life below Water) and 15 (Life on Land), and in transparent carbon accounting for NDCs.

Finally, two other international frameworks that rely heavily on LCT are the European Union Green Deal, and one of its building blocks, the Circular Economy Action Plan (CEAP) (see Figure 2.19). The EU Green Deal aims for climate neutrality by 2050 and the tackling of environmental challenges, while growing the EU into a fair, prosperous and resource-efficient society (Sala et al., 2021). Increased requirements for open information flow on the origins and end-of-life plans for products will reduce the problem of 'greenwashing', increasing confidence in product impact reporting and enabling a more circular economy. Tracking product impacts from cradle to grave requires robust and transparent LCAs. The CEAP supports this effort, calling for the utilization of LCA in public procurement particularly in the C&D sector, and the development of easier to use LCA calculators and tools for this industry (WBCSD, 2020).

In Ireland, the CEAP and the EU Green Deal have been key drivers to recent initiatives. The Waste Action Plan for a Circular Economy (WAPCE), released in 2020, aims to move Ireland from the old way of 'treating waste' in a linear take-make-dispose approach, to instead taking a 'resource' management approach, which includes an overall consideration of how materials and resources are consumed. C&D waste is the largest waste stream in both the EU and Ireland, although 80% of this waste is soil and stone (DCCAE, 2020). Blade material that enters the waste stream is considered C&D waste. The WAPCE calls for incentives for the use of recycled material and to build in 'thresholds' for Public Procurement, which further encourages GPP. According to *Project Ireland 2040*, the Irish population is growing at nearly double the OECD average, which is projected to lead to an additional 1 million people by 2040 (Irish Department of Public Expenditure and Reform, 2018). The *Climate Action Plan* (CAP), which outlines an Irish plan to be carbon neutral by 2050, cites *Project Ireland 2040's* call for population growth in a compact, connected and sustainable way as well as the SDG's cross-sector approach that climate action must be complementary to other important policy aims (DCCAE Ireland, 2019). Ireland will have a huge challenge to house, transport, educate and employ 1 million extra people, while simultaneously reducing waste, resource consumption and CO_2 emissions as called for in the CEAP and the CAP. Managing C&D activities will be key in achieving these reductions.

2.5.2 The Circular Economy

A circular economy is one in which no waste is generated, resources are circulated, and nature is regenerated, as defined and popularized by Dame Ellen MacArthur (Ellen MacArthur Foundation, 2021). The circular economy concept can trace its roots back to Kenneth Boulding's idea of spaceship earth, in which the measure of success of this 'spaceman economy' is based not on production and consumption, but rather on '*the nature, extent, quality, and complexity of the total capital stock, including in this the state of the human bodies and minds'* (Boulding, 1966). A few years later in 1972, 'Limits to Growth' concluded that, at the present trend, the limits of our world would be exceeded within 100 years unless the world changed its resource consumption pattern and instead chose to work toward establishing a condition of ecological and economic stability (Meadows et al., 1972). This idea was ridiculed at the time, and it would be some years later before the linear take-make-dispose approach to the economy was challenged again. Published in 2002, ‘Cradle to Cradle’ described the idea of remaking the economy to be regenerative like nature, and expanded on the idea of resource conservation to include human health and ecological aspects in product design (McDonough and Braungart, 2002). William McDonough, an American architect who grew up in Japan and Hong Kong, and Michael Braungart, a German chemist and one of the founders of Germany’s Green Party, combined their expertise to issue a call for the production of goods to mimic nature, where ‘waste’ becomes ‘food’ for another system. One of their Five Steps to Eco-Effectiveness involves the idea of ‘preferring respect’, which they claim to be at the heart of eco-design. Designers must remove from their design all chemicals or processes which could be harmful throughout the product’s lifecycle, thus demonstrating respect to the people who manufacture it, the communities who bear the burden of the by-products of manufacturing, the consumers who use the product and the people who will manage it at its end-of-life (McDonough and Braungart, 2002).

These concepts, from the idea that earth’s resources are finite and must be conserved, to mimicking nature’s circular and regenerative cycle, to respecting people by designing out harm, are all aspects of the Circular Economy. In the butterfly diagram (Figure 2.20), the left hand side represents the biological regenerative processes, while the right hand side is the product stock management processes. Flows that are closer to the centre, such as ‘Share’ or ‘Maintain/Prolong’ tend to require less energy or resources to achieve and are considered more circular, while flows that are further out, such as ‘Recycle’ tend to take more energy and are considered more linear. The Ellen MacArthur Foundation was created to share knowledge to inspire the creation of products and business models that operate in the more circular region. Ultimately, the circular economy approach can address both climate change and biodiversity loss, while at the same time growing prosperity, jobs, and resilience (Ellen MacArthur Foundation, 2021).

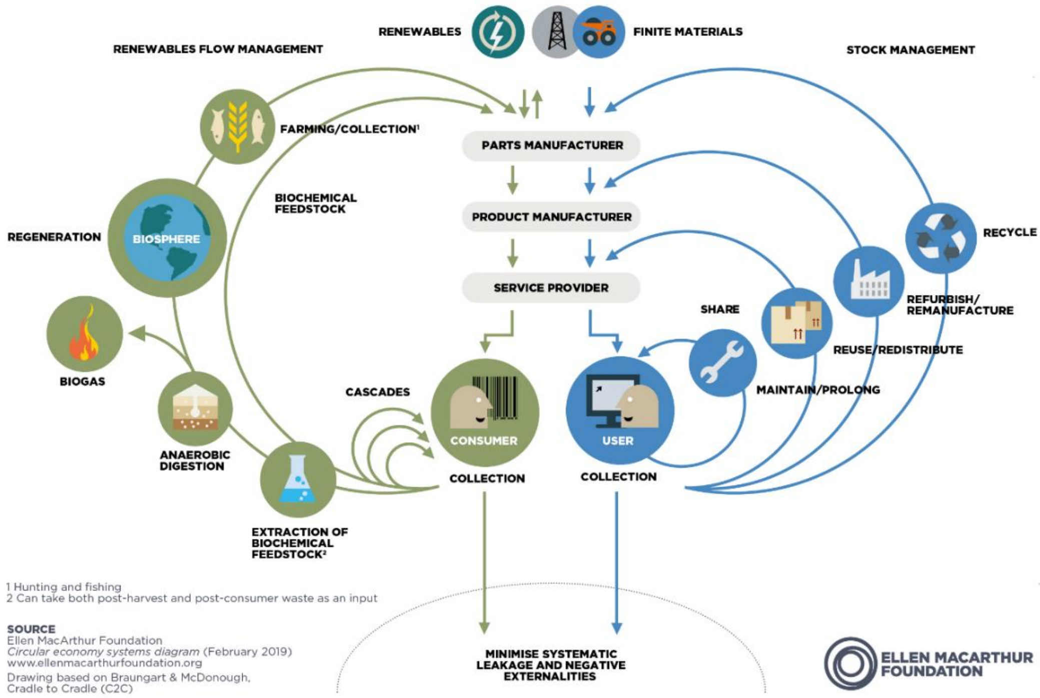

Figure 2.20 The Circular Economy Butterfly Diagram, as presented by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2021)

2.5.2.1 Circular Economy and Construction & Demolition Waste

Tackling C&D waste is at the top of the EU and Irish resource management agenda. Construction and Buildings is cited in the CEAP as one of the seven high-impact categories, with a plan to embed material recovery targets into modified business models (WBCSD, 2020). Waste from wind farms is categorised as C&D waste, and thus the method of dealing with End-of-life blades will be included in these metrics. In Ireland, the Department of Environment, Climate and Communications (DECC) is considering price based measures to encourage the use of recycled material in construction, the revenues of which will support circular economy initiatives (OECD, 2021). Although Ireland has the second lowest circularity rate in Ireland (Eurostat, 2018), projects are emerging that will improve this. One example is Limerick's Opera Site Project which is using best practice methods such as a pre-demolition audit to identify and assess materials that can be reused or recycled on site or in other local projects (OECD, 2021).

A 2020 study of 100 stakeholders in the UK construction industry showed that the main barriers to efficient recycling and re-use of C&D waste were logistics, cost, time, and regulations (Ghaffar et al., 2020). Many of the interviewees asked for policy to be put in place which requires a set percentage of the material in a project to be reclaimed. Having an industry-wide re-use requirement would allow them to bid competitively while ‘doing the right thing’. This was echoed by a 2021 study by the Chinese Ministry of Education in which inadequate governmental incentive and support policies and an insufficient legal framework were two of the top barriers to C&D waste circularity (Liu et al., 2021). It was noted that the stakeholders in UK construction appear to have little reason to innovate at the moment, as the market does not incentivize them to do so (Ghaffar et al., 2020). Other studies have shown a lack of balance between the supply and demand of recycled materials, whereby there is no incentive to reclaim material when there is no customer willing to pay to receive the material. A 2020 study from the perspective of potential C&D waste customers revealed the following barriers: a lack of standards and certifications, ineffective sorting and contamination, cost of materials, and negative public perception of reclaimed materials (Shooshtarian et al., 2020).

Much is being asked of governments to support circular economy in the C&D industry. Increasing confidence in the use of reclaimed C&D waste would require the development of quality certifications for materials, specifications around waste identification and sorting including the requirement to perform pre-demolition audits, and a relaxation in design codes to allow for the reuse of material (Ghaffar et al., 2020; Shooshtarian et al., 2020; Zhang et al., 2022). Local governments could drive demand by engaging in green procurement, as is called for in Ireland’s 2021 Climate Action Plan (Government of Ireland, 2021). Community awareness of reuse could be amplified when a project is publicly showcased whereby the utilization of reused materials is clearly visible (Ellen MacArthur Foundation, 2019), which would help to improve public perception of reclaimed material. Governments could support the development of technology such as robotic sorting and processing, and innovative approaches to remanufacturing, such as repurposing of structural members (Figure 2.21). All of these efforts to bolster the quality of and confidence in reclaimed material will lead to increased economic value, also called waste valorisation (ETIA Ecotechnologies, 2017; Kabongo, 2013), which will begin to balance supply and demand.

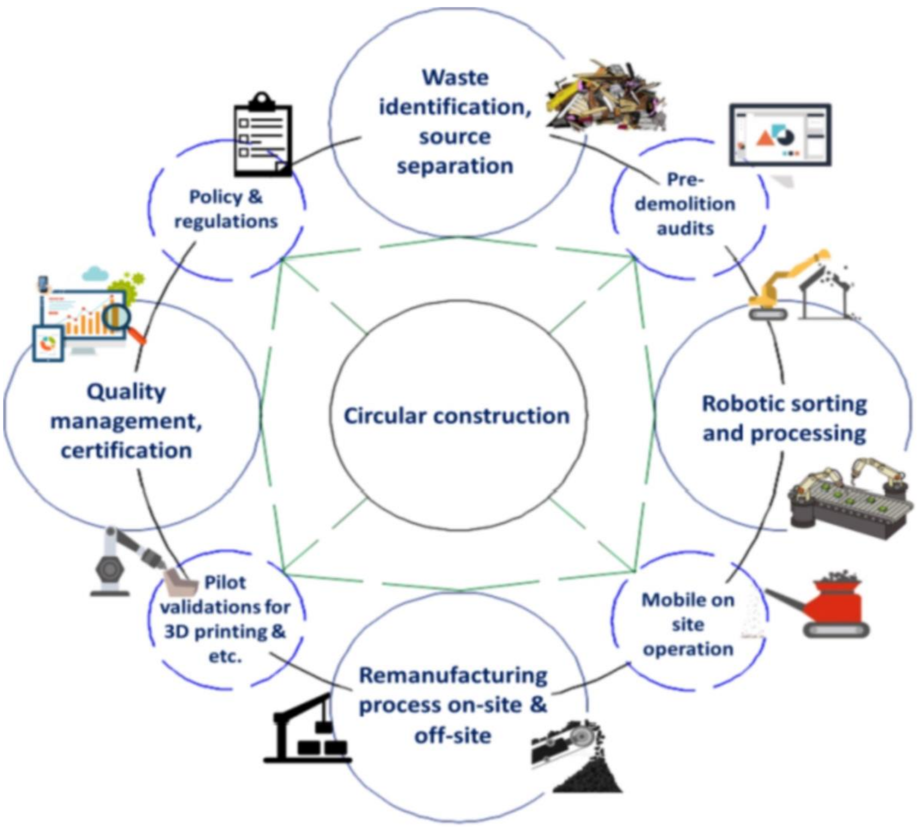

Figure 2.21 Concepts to enable the uptake of circular construction projects (Ghaffar et al., 2020)

2.5.2.2 Waste Valorisation and Job Creation

Waste valorisation is the process of converting a waste product into a beneficial, economically viable product through a recycling or repurposing process. Waste valorisation plays an important role in closing material loops, particularly for industrial production by-products where waste tends to be more homogenous and large-scale than from domestic waste sources (Nzihou and Lifset, 2010). An important requirement to waste valorisation is that the conversion process does not create harm through the release of toxic chemicals, as measured through LCA (Nzihou and Lifset, 2010). In addition, a UK report showed that jobs created from recycling industry are more geographically dispersed, potentially bringing jobs to lower income areas (Morgan and Mitchell, 2015; Shooshtarian et al., 2020). This is as compared to manufacturing jobs, which tend to be located in already existing manufacturing centres, thereby creating jobs in locations where there is already higher employment.

Therefore, creating jobs in the recycling sector has the potential to bring about more social improvements.

2.5.3 Introduction to Life Cycle Assessment

As introduced in section 2.5, life cycle assessment is a methodology for compiling and evaluating the inputs, outputs and potential environmental impacts across the lifespan of a product or process (ISO, 2006a). It aims to avoid burden shifting among both life cycle stages and impact categories. LCA first started with a focus on the impacts of beverage containers in the 1960's and 1970's, with Coca Cola commissioning one of the first known studies in 1969, and the US EPA publishing the first peer reviewed study in 1974 (Hauschild et al., 2019). The 1980's and early 1990's saw the development of inventory databases, impact assessments and a code of practice as the first effort to harmonize the LCA framework. This resulted in International Standards Organisation (ISO) 14040 (ISO, 2006a) & 14044 (ISO, 2006b) released before 2000, which established an internationally recognised framework for LCA. Around this time, the first versions of the widely used GaBi and SimaPro LCA software were released, to assist practitioners in the modelling of increasingly complex product systems (GaBi, 2012; PRé Sustainability, 2019a). The 2000's saw further refinement of the methodology, including distinctions between attributional versus consequential LCA (Weidema, 2003) and the inclusion of social and cost aspects into a Life Cycle Sustainability Assessment. In 2002, the United Nations Environmental Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) formed the UNEP/SETAC Life Cycle Initiative, a public-private multi-stakeholder partnership enabling the global use of credible life cycle knowledge by private and public decision makers (UNEP/SETAC, 2021). The ISO standards, Life Cycle Initiative website, LCA software and various LCI databases form the toolkit for LCA practitioners. LCA has become a well-established and trusted tool across many sectors for quantifying environmental impacts. The next few sections describe the use of LCA in some of these sectors.

2.5.4 LCA in the Wind Industry

The wind industry has used LCA to assess life time impacts of the manufacturing, use and end-of-life of wind turbines (Elsam Engineering A/S, 2004; Hanes et al., 2021;

Vestas Wind Systems A/S, 2006a, 2006b). These studies, when reported publicly, can give assurance that renewable energy technology is truly offering a net benefit. Equipment manufacturer Vestas produces a LCA report for many of their models which includes an energy balance calculation. An energy balance calculation is the period in which a turbine must operate to balance the energy consumed across its life cycle, after which the turbine has 'repaid' the energy required for manufacturing, transport, operations and maintenance, and end-of-life disposal. For example, energy balance on a Vestas V82-1.65 MW turbine is reached in 7.2 months, and the energy balance on a V90-3.0 MW is reached in 6.8 months (Vestas Wind Systems A/S, 2006b, 2006a). End-of-life modelling differed slightly between these two assessments. In both studies, 90% of the metal was recycled and 10% went to landfill. In the V82 study, 100% of the blade material was landfilled. However, the V90 study attempt to model what might happen to blades in the future, based on technology available now: incineration with heat recovery with the remaining glass fibre portion sent to landfill. A 2009 LCA of a 2 MW Gamesa wind turbine showed an 89% improvement on the impacts due to energy generated from this turbine, when compared against the electricity mix in Spain (Martínez et al., 2009). However, in the absence of any better alternatives, this LCA also assumed landfilling of the blades at end-of-life. Most academic and industry LCAs up until 2018 assume landfilling or incineration of blades at end-of-life (Sakellariou, 2018) or include nothing at all (Mishnaevsky, 2021; Ortegon et al., 2013).

2.5.5 LCA in Waste Management and Cement Processing

LCA is commonly used in decision making around waste management, and in particular the environmental performance of co-incineration of waste, as it allows assessment across the entire production chain (Galvez-Martos and Schoenberger, 2014). Co-incineration, or co-processing of waste derived fuels, is defined by the World Business Council as "Selected waste and by-products with recoverable calorific value which can be used as fuels in a cement kiln, replacing a portion of conventional fossil fuels, like coal, if they meet strict specifications. Sometimes they can only be used after pre-processing to provide 'tailor-made' fuels for the cement process" (WBCSD, 2005). Processing of waste material in a cement kiln for the purposes of deriving benefit from this waste material will thus be referred to as 'co-processing'.

Two approaches can be taken when conducting an LCA of co-processing in a cement kiln: 1) Assessing the impacts on the cement manufacturing process when utilizing waste material, or 2) Assessing the impacts due to the waste management option selected (Galvez-Martos and Schoenberger, 2014). The system boundaries, functional unit, time perspective, parameters considered, and data sources will be quite different with each approach (Ekvall et al., 2007). One brief example, the functional unit, defines the quantity of material that provides a specified function: Example (1) may define the functional unit as '1 tonne of cement produced', while example (2) may be 'the disposal of 1 tonne of waste.' Many co-processing LCA studies have been conducted by the cement companies or industry association, with approach (1) used to assess marginal impacts in clinker production due to the use of waste as fuel and raw materials (European Composites Industry Association, 2013; GTZ-Holcim, 2006). Chapter four of this thesis is a study of the use of blade waste in cement co-processing, in which approach (2) is used. A 2014 in-depth review of LCA studies of co-processing showed inconclusive results as to whether carbon and air emissions, and primary energy demand are reduced as a result of the use of waste material as fuel. However, it did show that reductions in the clinker factor, which could include a substitution of raw materials for clinker as is discussed in chapter four, or the reduction of the percentage of clinker incorporated into cement, does have a beneficial impact (Galvez-Martos and Schoenberger, 2014). Material substitution offers significant benefits when reusing or recycling waste material, but the modelling of this approach must be treated carefully (Rigamonti et al., 2009; Zink et al., 2016). Substitution of raw materials with waste material is more often driven by market factors, such as the availability and cost of waste material for an incineration plant as compared to standard fuel. Certainty in the modelling could be increased if the supply of waste material was well established and predictable (Vadenbo et al., 2017).

2.5.6 LCA & Circularity

Circular indicators and LCA do not always agree with each other. Adhering to a circular economy often dictates that the best choice is to keep material in circulation for as long as possible. However, this may not always be the most beneficial. Haupt and Zschokke (Haupt and Zschokke, 2017) state *'that it was demonstrated that the most circular solution is not necessarily the most environmentally preferable option'.*

However, circularity indicators could be masking a burden shift towards increased pollution or energy consumption. One suggestion was in choosing to 'Subordinate circularity metrics to LCA' (Rigamonti and Mancini, 2021). Circularity indicators are often easier to communicate to the public than LCA results, and thus play an important role in increasing CE awareness (Rigamonti and Mancini, 2021). A discussion on considering both LCA and Circular Economy metrics will be presented in chapter six.

2.6 Conclusions

This chapter has established the problem of a lack of benign, technically mature end-of-life options for wind turbine blade material. Blade waste amounts were estimated, and the case for repurposing of blade material at end-of-life was made. Repurposing efforts within the Re-Wind project were detailed, as well as large and smaller scale efforts by other groups. The cross-disciplinary nature of the Re-Wind group was introduced, and an argument was presented for the importance of developing transdisciplinary skills and research groups to solve difficult problems. The Embedded Systems Model of reality was suggested as a starting platform for understanding Life Cycle Thinking, and a brief history of European sustainability policy efforts was presented. Finally, an introduction to the Circular Economy and Life Cycle Assessment was given.

Clear gaps in the global literature emerged during this review. From the perspective of end-of-life wind blades, there appears to be no research consensus on the best practice in dealing with large quantities of this material. The end-of-life option of co-processing of the blades in a cement kiln has been suggested as best practice by the composites industry. However, no study has been completed comparing this end-of-life method to other disposal options such as incineration or landfill, utilizing LCA methodology. Likewise, few documented applied blade repurposing projects exist. Those that have gained publicity do not have publicly documented assessments of the environmental benefits or the process by which the blades were acquired and re-manufactured.

More broadly, few studies incorporating life cycle thinking and the SDGs exist, and no methodological framework exists for combining LCA, the SDGs, and circular design. Focusing in geographically on Ireland, the application of LCA is clearly needed in order to meet several Irish policies. However, there appears to be few C&D waste reduction projects planned in general, and a lack of LCA based tools in place that can help Ireland meet its Climate Action Plan goals.

Chapter three describes the overarching methodology used within the thesis. It details the life cycle thinking framework used in the quantitative research, including LCA and LCC, and the lesser- established Social Life Cycle Assessment (s-LCA) and Life Cycle Sustainability Assessment. Chapter three also describes the cross-disciplinary structure of the research project within which this thesis is conducted, and how the collaboration enriched this research.

3 Methodology

This chapter presents the overall methodology for the thesis. The methodologies for the individual studies will be discussed in detail in each of the relevant chapters. Life Cycle Assessment is used in all but one of the chapters, to quantify the environmental impacts of selected end-of-life and repurposing options. The island of Ireland is set as a geographically bounded case study for these studies. Chapter five incorporates a study of expected business opportunities bolstered by Irish and EU policy, along with field interviews to determine the acceptability of different designs. In chapter six, a field study is conducted on a pedestrian bridge built using wind blades, to collect material and cost data in order to perform an LCA and LCC. Stepping briefly back from the topic of repurposing waste in Ireland and the EU, chapter seven includes a study of the incorporation of the SDGs into business planning, and proposes a framework for selecting s-LCA indicators to support this. These indicators are combined in chapter eight with chapter six's LCA and LCC results to perform a full Life Cycle Sustainability Assessment of the blade bridge project. Table 3.1 presents a summary of these methodologies.

Overall, the research in each study is greatly informed by collaborative work within the Re-Wind project, which will be discussed next.

3.1 Context of Research in the Re-Wind Project

The research conducted for this thesis contributed to a larger project called 'Re-Wind'. Re-Wind is a multi-national consortium funded by the National Science Foundation (USA), Science Foundation Ireland (Republic of Ireland), and Invest Northern Ireland (United Kingdom). The project objective is to develop and compare sustainable end–of–life repurposing strategies for composite material wind turbine blades using a Geographic Information Science (GIS) platform coupled with environmental, economic and social Life–Cycle Assessments. The team was designed to be multicultural, gender balanced and multi-disciplinary, with researchers having backgrounds in Geography, Civil Engineering, Sociology, Business, Architecture, Structural Engineering, and Ecology.

Table 3.1 Methodology used by chapter

Chapter	Methodology Used
Chapter 4: A Comparative Life Cycle Assessment between Landfilling and Co-processing of Waste from Decommissioned Irish Wind Turbine Blades	Life Cycle Assessment (ISO, 2006a)
Chapter 5: Life Cycle Assessment of the Use of Decommissioned Wind Blades in Second Life Applications	Life Cycle Assessment (ISO, 2006a) Field Interviews
Chapter 6: Life Cycle Assessment and Life Cycle Costing of a Pedestrian Bridge made from Repurposed Wind Turbine Blades	Life Cycle Assessment and Life Cycle Costing (ISO, 2019) Field Interviews Field Study
Chapter 7: Sustainable Development Goals and Life Cycle Thinking as a Foundation to Developing Purpose Driven Businesses	Stakeholder identification using I-Corps™ method of customer discovery (Blank and Dorf, 2012) Social Life Cycle Assessment Guidelines (Benoît Norris et al., 2020)
Chapter 8: Sustainability Analysis of a Pedestrian Bridge made from Repurposed Wind Turbine Blades	Life Cycle Sustainability Assessment

To enable this research to fully tap into this diverse team's expertise, I created a diagram illustrating collaboration opportunities between the research areas in order to reach project deliverables. In Figure 3.1, each of the nodes represents a research area within the Re-Wind group. The lines between nodes represent project deliverables. The research areas and project deliverables were:

Business Models: Business assessment of the design ideas (from Product Design), taking into account blade material logistics (from GIS), policy implications, and product demand. Business ideas were fed into Life Cycle Assessment for environmental impact feedback.

Geographical Information Systems (GIS): Mapped wind farm locations, blade models, and temporal estimates for blade material availability. This information was fed into the Product Design node to help choose the blade model to use in designs. Blade locations guided some of the choice of Community Consultation efforts. Location and blade material fed into Life Cycle Assessment impacts due to transportation.

Community Consultation and Stakeholder Engagement: Assessed the acceptability of the designs generated by the group, and interviewed stakeholders in the wind energy sector, and blade product stakeholders. The Product Design node provided a catalogue of images to use in conducting community consultation. Results of early consultations informed social life cycle assessment indicators for Life Cycle Assessment.

Product Design: Collected ideas from the group, and developed these into designs and early prototypes. The mechanics node offered structural feedback of the designs. The Business Models node gave iterative feedback on the design ideas, which resulted in more robust scenarios for each design idea. Life Cycle Assessment offered iterative feedback on the designs and scenario creation.

Mechanics: Structural analysis and modelling of the product designs. Provided structural testing to support project prototypes, and bill of quantity information which Life Cycle Inventory Data was based on for Life Cycle Assessment.

Life Cycle Assessment: Iterative environmental feedback on the ideas generated by the group, to inform the Business Models, Product Design, and Prototyping nodes.

In this research, I became the project expert primarily for the area of Life Cycle Assessment. However, to answer the established research questions in this thesis, I had to become knowledgeable in Business Models and Stakeholder Engagement, and to collaborate closely with the remaining areas as well. Using Figure 3.1 as a base, the multi-, inter-, and trans-disciplinary approaches in each of the research chapters will now be described.

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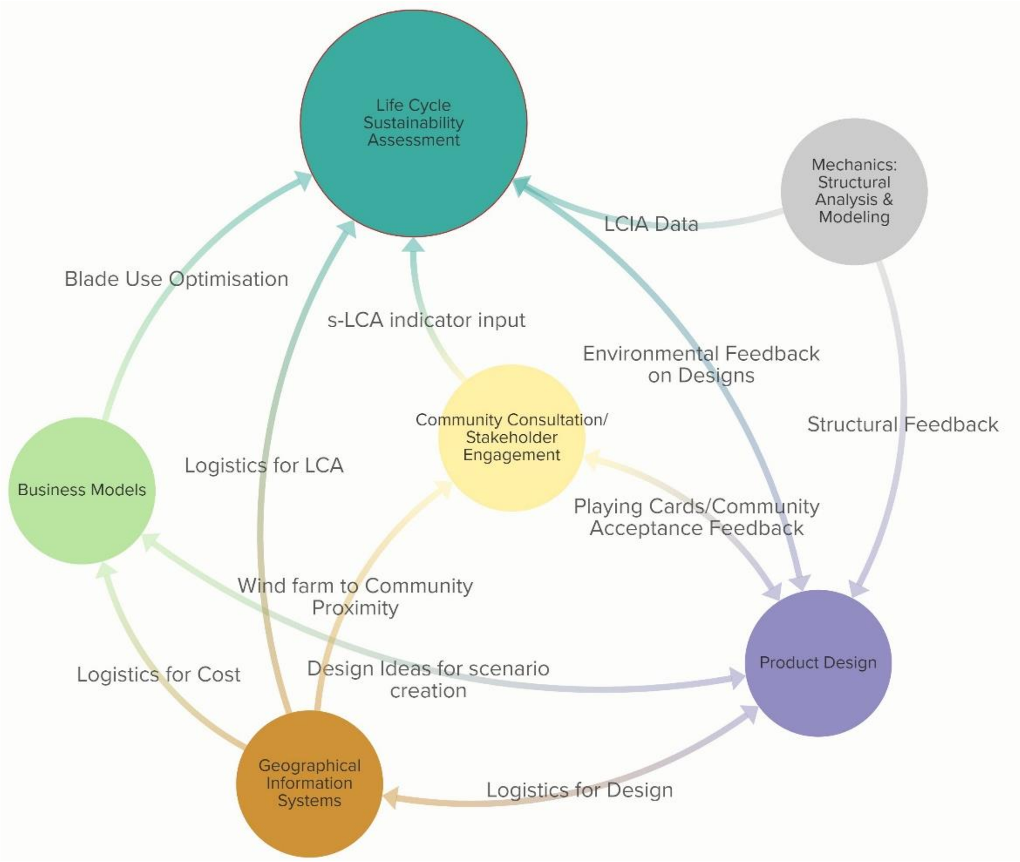

Figure 3.1 ReWind Project research nodes, and research deliverables by discipline

3.1.1 Disciplinary Research Approach by Chapter

Chapter four uses LCA to establish an environmental baseline for the end-of-life handling of blade material in Ireland. Blade models and locations were required in order to define a blade quantity with which to establish the functional unit and transportation distances. The GIS group created a dashboard of wind farm locations, which included blade models, weights, and estimated decommissioning dates (Delaney et al., 2021). I then used the dashboard to calculate blade mass and transport distance, which I used to establish the functional unit for this study, and perform the LCA (Figure 3.2). The research for this chapter was multi-disciplinary as the goal of my research was separate from the GIS group's research goals.

Figure 3.2 ReWind research areas utilized in chapter four

Chapter five develops three repurposing scenarios for Irish blade material based on optimizing environmental improvements. This study required collaboration with three other areas (Figure 3.3). First, a review is conducted of all designs in the Re-Wind Design Atlas (Bank et al., 2018b), which was generated by the Product Design group. This review was based on each design's potential to result in environmental benefits due to the substitution of raw construction material with blade material, as assessed by LCA. Next, I incorporated some of the aspects of the Business Models research area by doing early assessment of business viability based on EU and Irish policy encouraging 'green' businesses, and conducting field interviews of stakeholders. Feedback from these field interviews contributed to the creative process of the next revision of the Product Design group's Atlas, called the Re-Wind Catalogue (McDonald et al., 2021). Finally, turbine type and location from the GIS group allowed the full formation of the scenarios by informing transportation logistics and the choice of a remanufacturing location per scenario. The research for this chapter is transdisciplinary, as the research objective was 'to optimize environmental impact reduction by repurposing decommissioned blade material', which required an iterative flow of design feedback between the product design group and myself, and required me to switch into considering Business Model and Stakeholder engagement aspects to help in creating scenarios that would optimize blade use, while performing iterative LCAs to calculate impact.

Chapter six conducts an LCA and LCC of the applied case study of the pedestrian BladeBridge, and assesses potential business viability of this product. This study again required collaboration with Product Design and research in the area of Business

Models, with the addition of the Mechanics area and Community Consultation (Figure 3.4).

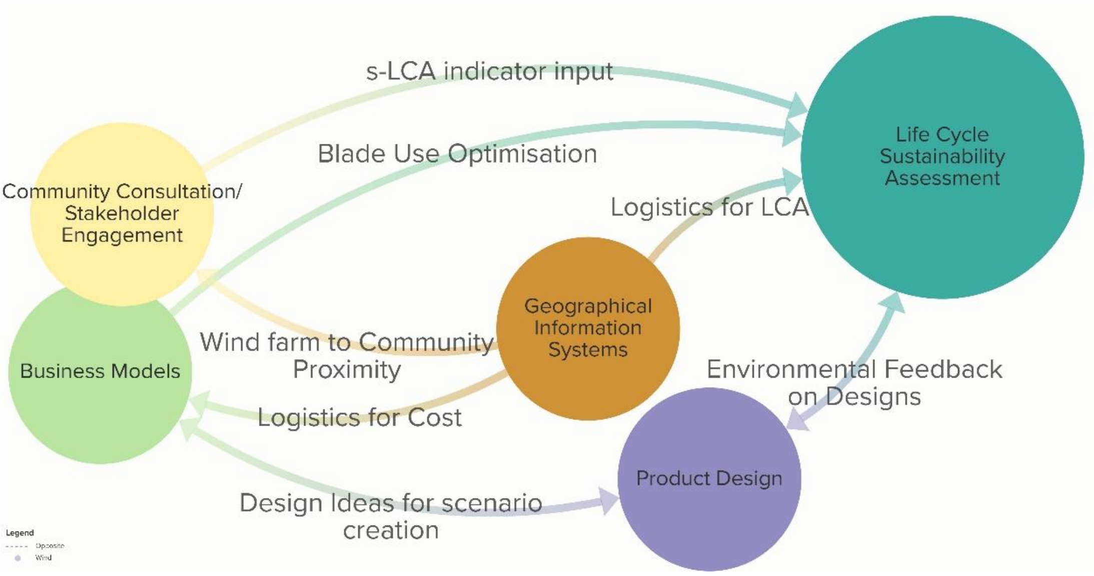

Figure 3.3 ReWind research areas utilized in chapter five

An early study done by the Mechanics group indicated that the blades would be structurally sufficient for use as a pedestrian bridge (Suhail et al., 2019). At the same time, another study by the Community Consultation group indicated that bridges would be well received by community groups, including groups opposed to local wind farm developments in close proximity to wind farms (Gough, 2022). Within the Business Models area, I conducted field interviews of both wind farm owners and public procurers of bridges in order to make an early assessment of business viability. Finally, iterative collaboration with the Mechanics group helped informed the design of the pedestrian bridge, and Life Cycle Inventory data was gathered from the BladeBridge bill of quantity, as generated from the design. This research for this chapter was interdisciplinary, as inventory data was supplied to me by the Mechanics and Product Design groups, while I fed back environmental assessment data which informed the design process.

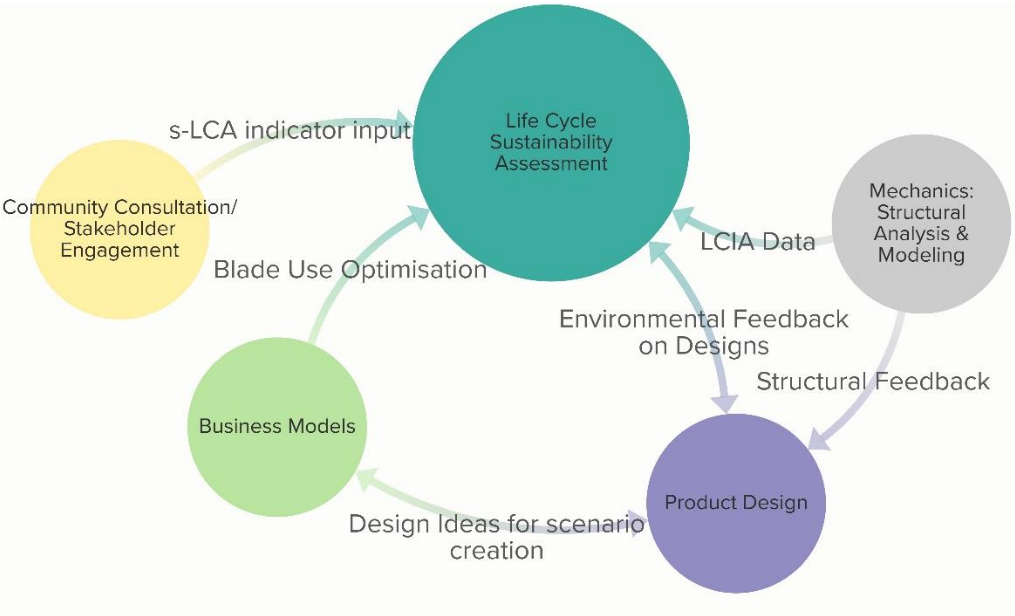

Figure 3.4 ReWind research areas utilized in chapter six

Chapter seven establishes a set of social-LCA indicators with which to assess the BladeBridge product. This study required stepping more into the Life Sciences to learn about sustainable communities within the Community Consultation/Stakeholder Engagement area. Learning about the SDGs informed the s-LCA indicator selection (Figure 3.5). These indicators are designed to then be used in conjunction with LCA and LCC, to assess a product's ability to contribute to a 'purpose driven business.' The research for this chapter was multi-disciplinary, as the information gathered by the community consultation group was simply referenced in order to inform my research.

Figure 3.5 ReWind research areas utilized in chapter seven

Chapter eight includes a full Life Cycle Sustainability Assessment of the pedestrian BladeBridge, as well as an assessment of the product's ability to contribute to a purpose driven business. Research from chapters six and seven were brought together, which includes all of the six areas of Re-Wind research (Figure 3.6). The research for this chapter was transdisciplinary, as it aimed to answer the question 'Is the BladeBridge product worth making', and the study required me to understand business model development, LCA and social aspects of the SDGs, while collaborating with the Mechanics and Product Design groups.

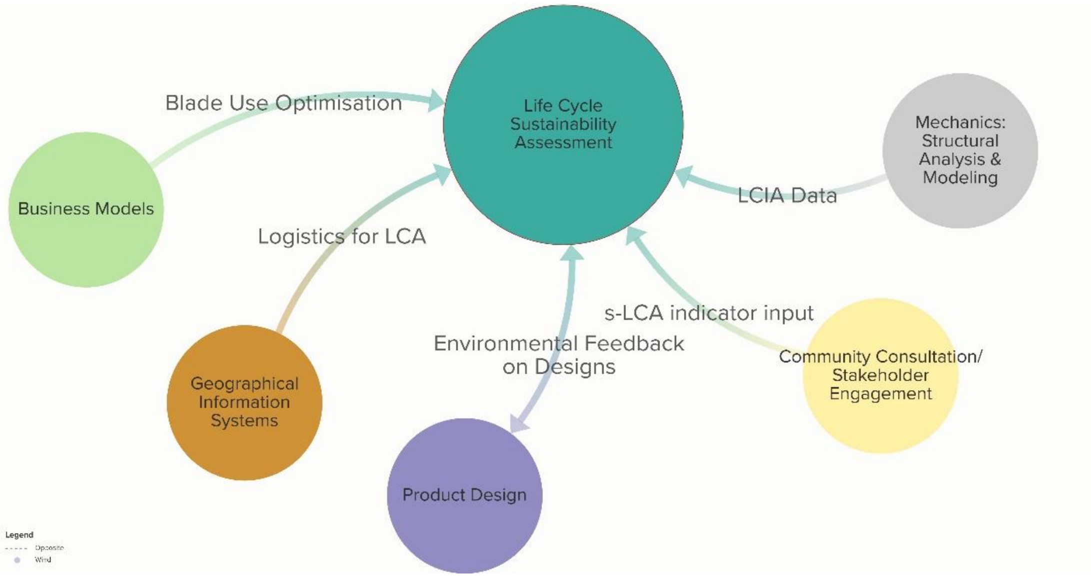

Figure 3.6 ReWind research areas utilized in chapter eight

3.2 Life Cycle Sustainability Assessment

Next is a description of the methodology of each of the three frameworks within the LCSA.

3.2.1 Life Cycle Assessment

The framework of LCA was heavily used in this thesis, and therefore an overview of the methodology will be discussed here .

LCA addresses the environmental aspects and potential impacts throughout a product's lifecycle, including raw material extraction, manufacturing, transportation, use, and end-of-life treatment (ISO, 2006a). All of the inputs and outputs across a product's lifecycle, as defined by set system boundaries and a functional unit, are quantified and assessed for their impact to the environment. The LCA framework ensures that changes or improvements made in one geographical location, or in one impact category, do not inadvertently shift the burden into another location or category. This holistic accounting of impacts is an essential part of life cycle thinking.

LCA is defined by ISO 14040 and 14044, which define four phases in a LCA study (Figure 3.7):

1. Goal and Scope Definition
2. Inventory Analysis
3. Impact Assessment
4. Interpretation

Step one of an LCA is to define the Goal and Scope of the study. The goal is simply the reason for conducting the study: what it is the practitioner would like to discover, the intended audience, and whether the study will be used publicy in order to compare products or processes. The scope defines the product system and function to be studied, and system boundaries. A functional unit is established in order to compare two systems with equivalent functions. An example of a functional unit comparing end-of-life options for wind turbine blade waste might be 'the disposition of 1 tonne of GFRP blade waste in Ireland for 60 years'. Inputs and outputs of different systems with equivalent functions will likely be different, therefore the functional unit is critical in establishing the reference flow of inputs and outputs across the system, as defined by the system boundaries..

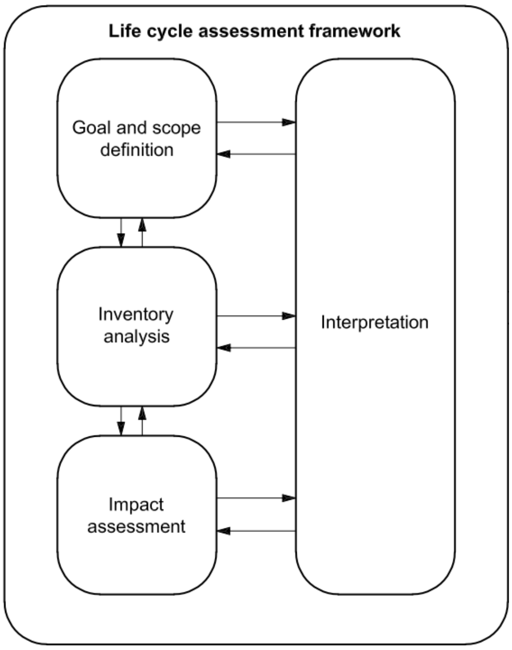

Figure 3.7 Stages of an LCA, per ISO 14040 (ISO, 2006a)

System boundaries define the temporal, geographical and technological aspects of the study. It is important to be transparent about assumptions made for allocating or omitting certain flows (ISO, 2006b), as this step can have the single largest impact on the overall LCA results. It is useful to draw a system boundary diagram to help visualise which flows will be included and how waste material will be allocated, such as in chapter four, Figure 4.2. The functional unit in conjunction with the system boundary allows the calculation of the process flows into and out of a product system, which are utilized in the next step of the LCA. Process flows can include energy and material inputs, and waste material outputs.

Step two of an LCA is the Life Cycle Inventory (LCI) Analysis. The process flows established in the previous step are first converted into ‘elementary flows’, defined as material or energy entering or leaving the system without previous or subsequent transformation (ISO, 2006b). The conversion to elementary flows are predominantly done through the use of an LCI database such as Ecoinvent (Wernet et al., 2016). The ecoinvent database was initially developed in the 1990’s and is based on many person-years of data collection over the past 30 years. The database provides the backbone of a LCA, also called the ‘background’ data, which is estimated to make up 99% of the elementary flows of most LCAs (Wernet et al., 2016). This allows the LCA practitioner to focus their time on the ‘foreground’ elements of the assessment, or the elements in which a change can be controlled, such as process or material changes. Elementary flows can include elemental emissions to air, water and soil,.

Step three of an LCA is the Impact Assessment, which quantifies the magnitude and significance of the environmental impacts due to the elementary flows, calculated in step two. To convert elementary flows into environmental impacts, conversion calculations, called characterization factors, are utilized. These calculations are contained within life cycle impact assessment (LCIA) methodologies, of which there are nine recommended for use in Europe (Joint Research Centre, 2011). The next section will review the selection process for the LCIA for this thesis, and then will return to an explanation of characterization factors.

Selection of an impact assessment methodology requires a comparison of the goal of the study, as established in step one, against the impact categories, indicators and characterization offered by the impact assessment. Assessments can be done at midpoint or endpoint. Midpoint are single Impact Categories (Figure 3.8) such as human toxicity or global warming and indicate an area of concern that is imposed upon the environment due to the elementary flows of the measured process. Endpoint or Damage categories, as indicated by the name, describes damages that the impacts cause an end point categories such as Human Health, Ecosystem Quality, Climate Change and Resources. Different LCIA methods use either midpoint, endpoint, or both in their reporting. The choice of LCIA can make a big impact on the results of an LCA, therefore the method should be chosen with consideration of the goal of the study. The next paragraph outlines the decision-making processing in selecting the LCIA which is used for the remainder of the chapters.

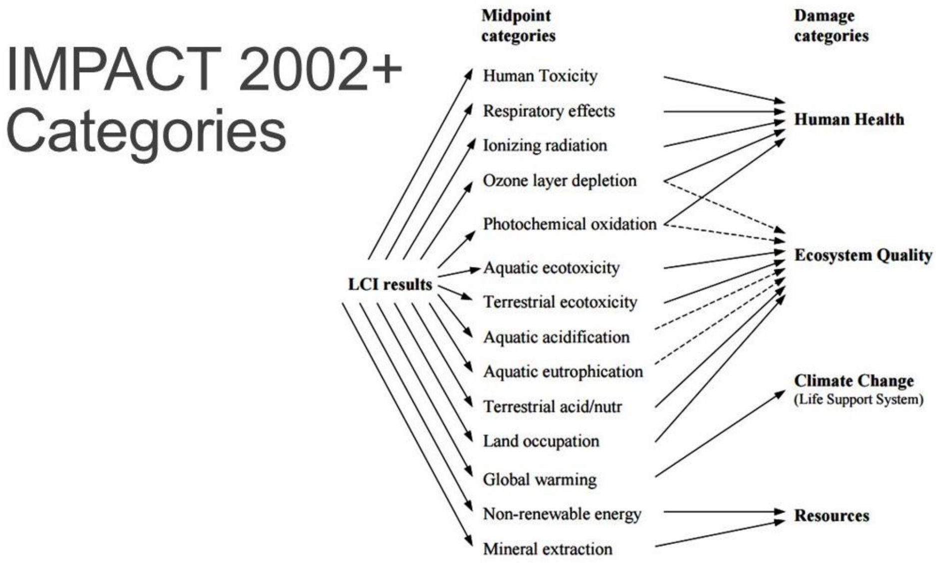

Figure 3.8 Framework for IMPACT 2002+ Life Cycle Impact Assessment, showing impact and damage categories

The International Reference Life Cycle Data System (ILCD) has released a series of handbooks describing the many LCIA methods (Joint Research Centre, 2011, 2010). To choose the LCIA for this thesis, all methods were reviewed based on their reliability in each impact category, and against criteria required of a LCIA methodology for this thesis. The criteria are:

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

These criteria are selected based on the overall focus of this thesis on the production of renewable energy in Ireland with the intended goal of reducing global warming, and the need to compare multiple end-of-life scenarios for blade material.

The recommended method for assessing the midpoint analysis of Global Warming Potential was IPCC's GWP, and Ecoindicator 99. Meanwhile, EPS2000, ReCiPe and LIME were selected as the best methods for endpoint level assessment, and scenario comparison (Joint Research Centre, 2011). The IPCC's GWP method is a 'single issue' method that only looks at climate change impacts, and the LIME method is mainly applied in Japan (Joint Research Centre, 2010), therefore, these two methodologies were eliminated. EPS2000 has been superseded by EPS2015d, and the current ReCiPe model is ReCiPe2016. Eco-indicator99 has been superseded by IMPACT2002+, a combination of IMPACT 2002, Eco-indicator99, CML and IPCC, which is favourable in that it has incorporated the best method for midpoint analysis of Global Warming Potential. Therefore, the top three LCIA methods against the set criteria are IMPACT2002+, ReCiPe2016, and EPS2015d. To further narrow down the LCIA choice, each method's unique features were reviewed (Joint Research Centre, 2010):

IMPACT2002+ is specially designed for comparative analysis, which will be useful in conducting LCAs for various end-of-life scenarios. It is European based, and as mentioned above, incorporates several other methodologies.

ReCiPe2016 combines midpoint and endpoint analysis, and all indicators have been well researched with supporting peer reviewed papers.

EPS2015d uses monetisation weighting, and could be incorporated with Life Cycle Costing (LCC) easily. Business as usual is the default scenario, which results in high damage factor for resource depletion.

For this thesis, we will choose IMPACT2002+ for its special feature of comparative analysis, and its incorporation of the IPCC global warming impact category. For all LCA's in this thesis, the LCIA IMPACT2002+ is utilized.

This section returns to the topic of characterization factors, to describe the method in which the selected impact assessment connects the elementary flows calculated in the LCI step, to the impact and damage category results. IMPACT2002+ includes 14 Impacts, or Midpoint categories, and four Damage, or endpoint categories (Figure 3.8

and), which can be considered the next two points in the cause-and-effect chain due to the elementary flows associated with a product system.

Characterization factors were developed for over 1500 different inventory results by the IMPACT2002+ team (Verones et al., 2020). Characterization factors are used to convert not only elementary flows into impact categories, but also to convert impact results to damage categories, and to normalize and weight the damage category results for aggregation into a single score result. The single score result is most widely used in this thesis, as a high-level comparator of scenarios.

To develop a characterization factor for a particular impact category, a reference substance must first be selected. This substance may be considered the top contributor to the impact category, and must have data compiled on the fate, exposure and effects modelisation with a high level of certainty. An example of a reference substance is the use of CO_2 for global warming. Characterization factors are then calculated for every substance that contributes to that impact category, as compared to the reference substance, using the broad calculation of multiplying chemical fate by exposure levels. The units of the characterization factors are typically kilogram-equivalents of the reference substance, or in MJ (see Figure 3.9 under the category Midpoint Reference Substance).

[source]	Midpoint category	Midpoint reference substance[4]	Damage category	Damage unit	Normalized damage unit
[a]	Human toxicity (carcinogens + non-carcinogens)	kg Chloroethylene into air$_{\text{-eq}}$	Human health	DALY	point
[b]	Respiratory (inorganics)	kg $PM_{2.5}$ into air$_{\text{-eq}}$	Human health		
[b]	Ionizing radiations	Bq Carbon-14 into air$_{\text{-eq}}$	Human health		
[USEPA and b]	Ozone layer depletion	kg CFC-11 into air$_{\text{-eq}}$	Human health		
[b]	Photochemical oxidation (= Respiratory (organics) for human health)	kg Ethylene into air$_{\text{-eq}}$	Human health		
			Ecosystem quality	*n/a*	*n/a*
[a]	Aquatic ecotoxicity	kg Triethylene glycol into water$_{\text{-eq}}$	Ecosystem quality	PDF·m^2·y	point
[a]	Terrestrial ecotoxicity	kg Triethylene glycol into soil$_{\text{-eq}}$	Ecosystem quality		
[b]	Terrestrial acidification/nutrification	kg SO_2 into air$_{\text{-eq}}$	Ecosystem quality		
[c]	Aquatic acidification	kg SO_2 into air$_{\text{-eq}}$	Ecosystem quality		
[c]	Aquatic eutrophication	kg PO_4^{3-} into water$_{\text{-eq}}$	Ecosystem quality		
[b]	Land occupation	m^2 Organic arable land$_{\text{-eq}}$ · y	Ecosystem quality		
	Water turbined	inventory in m^3	Ecosystem quality		
[IPCC]	Global warming	kg CO_2 into air$_{\text{-eq}}$	Climate change (life support system)	kg CO_2 into air$_{\text{-eq}}$	point
[d]	Non-renewable energy	MJ or kg Crude oil$_{\text{-eq}}$ (860 kg/m^3)	Resources	MJ	point
[b]	Mineral extraction	MJ or kg Iron$_{\text{-eq}}$ (in ore)	Resources		
	Water withdrawal	inventory in m^3	*n/a*	*n/a*	*n/a*
	Water consumption	inventory in m^3	Human health	(DALY)	(point)
			Ecosystem quality	(PDF·m^2·y)	(point)
			Resources	(MJ)	(point)

Figure 3.9 Main sources for characterization factors, reference substances, and damage units used in IMPACT 2002+ (Humbert et al., 2014)

Damage characterization factors, also called damage factors, are calculated differently for each of the four categories. For Human Health, the damage factor is broadly calculated by multiplying intake fractions, dose-response slope factor, and severity, which gives an estimation of the combination of mortality and morbidity, expressed in the units disability adjusted life years (DALYs) (Jolliet et al., 2003). Ecosystem quality is similarly calculated, with the severity calculations scaled to species rather than humans, and the fate model based on chemical concentration in water for aquatic effects (Jolliet et al., 2003). Ecosystem quality is expressed in potentially disappeared fractions per meter squared of land per year (PDF * m^2 * y). Climate change is directly taken from the impact category Global Warming, and therefore requires no characterization factor. The damage factor for resources is based on the amount of energy required to extract certain minerals and is expressed in megajoules (MJ). The next two steps in the impact assessment of normalising and weighting/aggregating are considered optional, based on the ISO standard (ISO, 2006a). Chapters four, five and six of this thesis use normalising and aggregation, and thus a description is included here.

Normalising is done by taking the total impact of a specific category divided by the total annual impact of all European contributions to that impact category. Normalisation facilitates interpretation of results by allowing the comparison of the impacts and damages between multiple categories.

Weighting can be performed after normalisation, although a weighting score of one was utilised in this thesis. The final step that can be used is aggregation od the data into a single score assessment. In this step, the normalised and weighted scores from the four damage categories are collected into one single score (Humbert et al., 2014). This single score assessment was used in chapters four, five, six and eight as a single comparator to show which scenario offered the least overall environmental impact.

3.2.2 Life Cycle Costing

Life-cycle costing has been in use well before LCA, dating back to use in 1960's by the United States Department of Defence (Hunkeler et al., 2008). LCC aims to quantify the cost of a product throughout its lifetime, including acquisition, operations and maintenance, and end-of-life costs, and is primarily used on long-lasting items with high investment costs (Hunkeler et al., 2008). LCC can be used in public procurement, to ensure products with the lowest lifetime costs are selected, rather than simply the lowest acquisition cost. When combined with LCA, the two together can identify economic and environmental hotspots in high value civil engineering works, among other products.[1]

Specifications have been developed to combine LCA and LCC which include setting the same boundaries and functional unit for each study (ISO, 2019). It is essential that

[1] Note that in this thesis, LCC calculations do not include costing of external environmental impacts.

both the LCA and LCC refer to a consistent definition of the product system, and that the cut-off criteria for one study does not inadvertently omit an important input from the other study (Swarr et al., 2011). An example of this in a civil engineering research project might be the high cost of the initial research and development labour cost, which has minimal corresponding environmental impact. These activities might have fallen below the cut-off criteria for an LCA, but contribute significantly to the LCC, and thus would need to be included in both studies in order to keep the scope and boundaries matched.

Civil engineering works life cycle information within the system boundary																	
A0	**A1-A3**			**A4-A5**		**B1-B8**						**C1-C5**					**Optional supplementary information beyond the system boundary**
PRECONS-TRUCTION	**PRODUCTION STAGE**			**CONSTRUC-TION STAGE**		**USE STAGE**						**END OF LIFE STAGE**					
Land and associated fees / advice	Raw material supply	Transport and all upstream processes from cradle to gate	Manufacturing of products	Transportation to the site	Construction of the civil engineering works	Use	Maintenance	Repair	Replacement	Refurbishment	Use of energy resources, use of material resources, use of water and waste management from the operation of the civil engineering works	Deconstruction / Demolition	Transport to waste processing or disposal	Waste processing	Disposal of waste	Re-landscaping	Potential net benefits from reuse, recycling and/or energy recovery, beyond the system boundary
				Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario
A0	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6-B8	C1	C2	C3	C4	C5	D

Figure 3.10 Life cycle stages for civil engineering works, per ISO 21931-2 (ISO, 2019)

ISO 21931-2:2019 also defines categorization of each lifecycle step (Figure 3.10) which include Pre-Construction, Production, Construction, Use, End-of-Life and Potential net benefits from post use recovery (ISO, 2019). Assessing costs and environmental impacts at this granularity can help to identify hotspots in the lifecycle or support a change in design or in the procurement decision making process. Finally, there is no impact assessment phase in an LCC like in an LCA, and no need for characterization or weighting.

ISO 21931-2:2019 is used in chapter six to combine LCA and LCC for the study of the BladeBridge.

3.2.3 Social Life Cycle Assessment

Social life cycle assessment is a methodology to assess the social impacts of a product or service throughout its lifecycle (Benoît Norris et al., 2020). S-LCA follows a stakeholder approach in defining the scope and impact categories, because effects on people (stakeholders), by definition, are what social impacts are. In the 2020 Guidelines for Social Life Cycle Assessment of Products and Organisations, the following stakeholder categories were defined, based on discussion with involved experts (Figure 3.11): Worker, Local Community, Value Chain Actors, Consumer, Society, and Children. Practitioners are encouraged to adhere to these categories when conducting an s-LCA, to facilitate comparisons. The system boundary and functional unit can be defined in the same manner as LCA and LCC.

Stakeholder categories	Worker	Local community	Value chain actors (not including consumers)	Consumer	Society	Children

Figure 3.11 List of stakeholder categories for s-LCA (Benoît Norris et al., 2020)

The Guidelines also call out the connection that s-LCA has with the SDGs, in that 14 of these 17 goals concern social impacts (Benoît Norris et al., 2020). In chapter seven, the categories defined in Figure 3.11 are used to identify specific stakeholders involved with both blade material dispositioning and the construction of a BladeBridge. These stakeholders are then used to screen socially based SDGs in order to develop s-LCA sub-indicators for use in a Life Cycle Sustainability Assessment.

3.2.4 Life Cycle Sustainability Assessment

An LCSA aims to provide a holistic perspective to sustainability assessments (Valdivia et al., 2013). However, LCSA methodologies vary considerably, with some studies fully incorporating all three into multi-criteria decision making (MCDM) tools, and others studying the three separately (Kühnen and Hahn, 2017). Many studies use a highly operationalized, additive approach based on the three-pillar approach to sustainability (Figure 3.12).

This requires the three dimensions to be 'standardized, harmonized, and synchronized' and then added together, which is less transparent and potentially misses many of the qualitative interactions between the three dimensions (Zeug et al., 2020).

This approach also does not take into account the reality discussed in the Literature Review, that the economy is embedded in society, which is embedded in the environment. Chapter eight moves beyond the additive or three pillar approach to LCSA towards an integrated, embedded systems model approach to sustainability, which more accurately reflects this reality.

Figure 3.12 Three pillar approach of sustainability (World Steel Association, 2020)

3.3 Conclusions

This chapter discussed the method in which cross-disciplinarity was incorporated into the research, within the opportunity offered by the Re-Wind project. The life cycle assessment framework and methodology were introduced, as well as life cycle costing, social life cycle assessment, and life cycle sustainability assessment. The next chapter delves more into life cycle assessment, which is used to compare various end-of-life options for Irish blade waste.

4 A Comparative Life Cycle Assessment between Landfilling and Co-Processing of Waste from Decommissioned Irish Wind Turbine Blades

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Abstract

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 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. 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.

KEYWORDS: Life Cycle Assessment, composites, waste, cement manufacture, wind turbines[2]

4.1 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 Ireland, 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.

[2]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

The European Waste Hierarchy (European Commission, 2008a) illustrates the preferred waste management processes, based on sustainability, with the most preferred option at the top. Figure 4.1 shows 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.

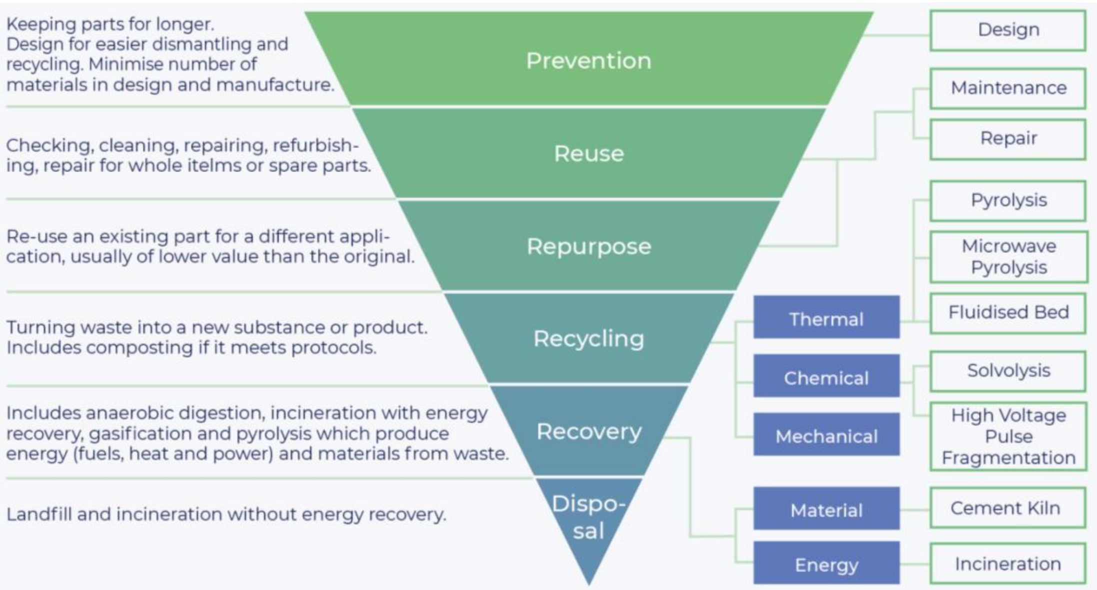

Figure 4.1 European Waste Hierarchy, in the context of wind turbine blade End-of-life (Ierides et al., 2018)

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 40mm 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.

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, 28^{th} 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, 28^{th} 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 life span, decommissioning dates were predicted using known commissioning dates (thewindpower.net). The results indicate that approximately 500 turbines are expected to decommission 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 A/S, 2006b), 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 A/S, 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 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 steam is handled in the most environmentally sound manner.

4.2 Methods

4.2.1 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 850kW and has three 25m blades that weigh 1900 kg each (Vestas Wind Systems A/S, 2006c). 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 1.5m^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 dismantling and cutting of blades into 1.5m^2 pieces are 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).

4.2.1.1 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.

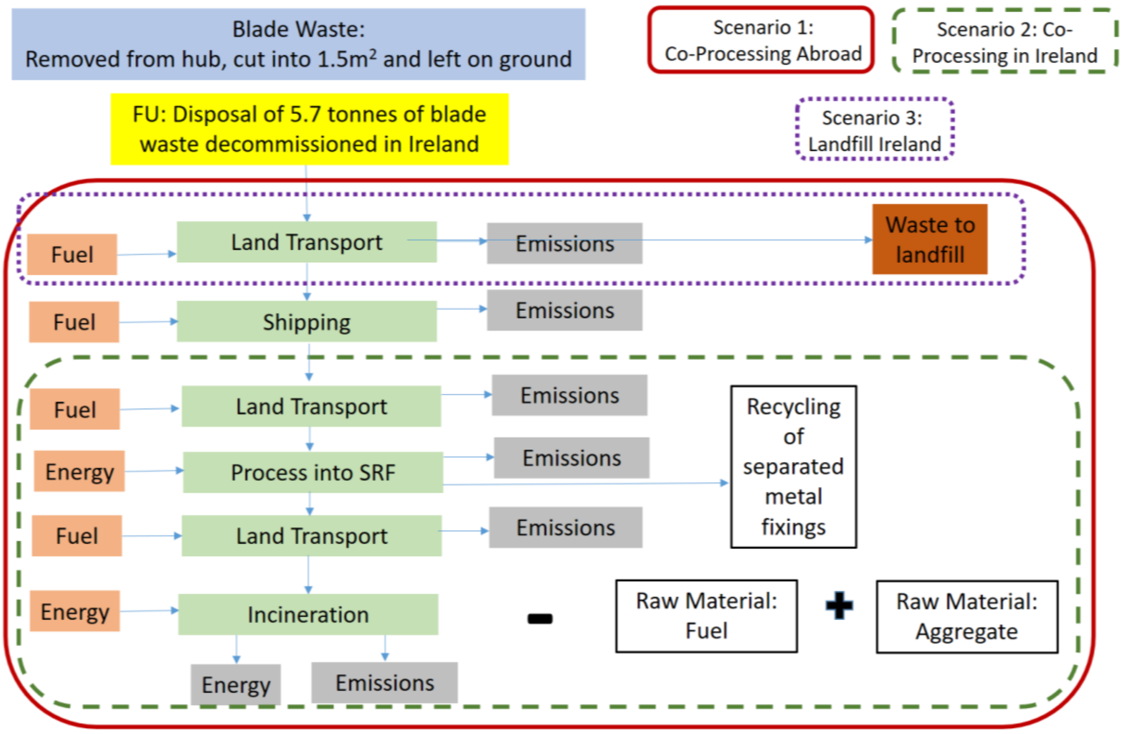

Figure 4.2 LCA Boundaries for Scenarios 1, 2 and 3

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.

According to an Irish waste management company, blades are cut on site into $1.5m^2$ 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 <40mm 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 (Figure 4.2).

4.2.1.2 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 <40mm 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 (Figure 4.2).

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.

4.2.1.3 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 (Figure 4.2).

4.2.2 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 and Branner, 2010) and composite outer layers (Figure 4.3) . The composite is a glass fibre mat impregnated with epoxy resin, manufactured using prepreg technology (Vestas Wind Systems A/S, 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.

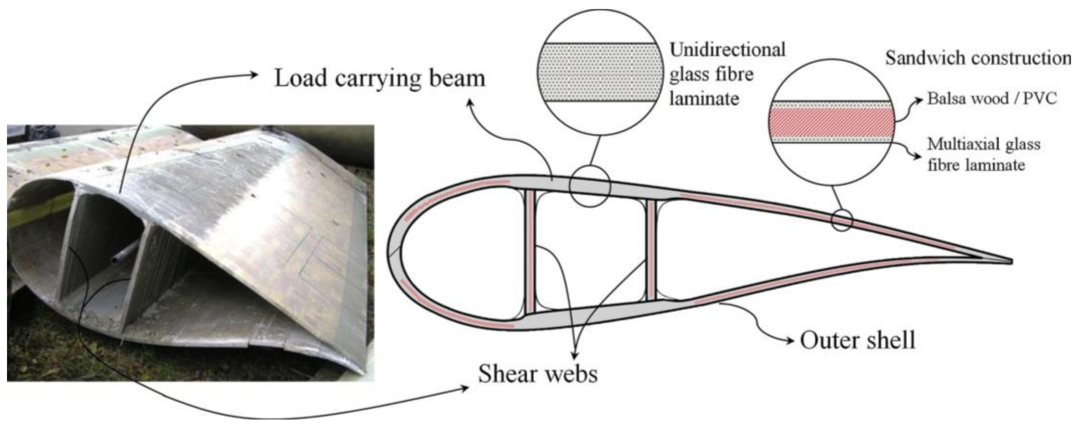

Figure 4.3 Cross section of a typical wind turbine blade (Beauson et al., 2016).

4.2.2.1 Metals

The metal components are the steel bolts for connection of the blade to the hub, and the copper lightening conductor and blade tip cap. The percentage of total mass varies from 2-8%, 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.

4.2.2.2 Foam and Adhesive

V52 blades contain a foam core in the skin and shear-web (Sørensen and Branner, 2010). 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).

4.2.2.3 GFRP Composite

Table 4.1 Mass calculations for components in one V52 blade

Component	% Total Weight	Total Mass in 5700kg Blade Waste (kg)	Mass of substituted material
E-Glass	(total 56%)	(total 3192)	Equivalent amount of material substituted
CaO	19.6%	1083	
SiO_2	30.8%	1767	
$Al_2O_3 + Fe_2O_2$	5.6%	342	
Epoxy	30%	1710	(1710 + 513) * 0.6 kg coal/kg blade material = 1334 kg coal
Foam & Adhesive	9%	513	
Metal	5%	285	All metal recycled

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 (Elsam Engineering A/S, 2004; 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 4.1.

4.2.2.4 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. Regarding fuel replacement quantities, one study shows that each 1000 kg of blade waste can replace 600 kg of coal (Liu et al., 2019). 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 4.2). Cement requirements and E-glass component data come from Holcim Deutschland Group Environmental Data Document (Hahn, 2017).

Table 4.2 Material Components required for cement production (Hahn, 2017)

Material Component	Cement components	E-Glass components	% of each component in blade waste (56% of blade waste is E-glass)
CaO	65-75%	32-38%	19.6%
SiO_2	21%	52-58%	30.8%
Al_2O_3 + Fe_2O_2	6-11%	5-15%	5.6%

4.2.2.5 Transportation Inputs

A windfarm in the Northwest of Ireland was 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 4.3 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 vary.

Table 4.3 Transportation distances for all three scenarios

Scenario	Transport Point to Point	Transport Type	Distance	5.7 tonnes * Distance (tkm)
1	Wind Farm to Dublin Port	6-8 tonne truck	200km	1,140 tkm
1	Dublin Port to Port of Bremen	Shipping liner	916nautical miles (1696km)	9,667 tkm
1	Bremen to Lägerdorf	Standard Tautliner Trailers	147km	838 tkm
2	Windfarm to SRF Pre-processing site	6-8 tonne truck	86km	490 tkm
2	Pre-processing to cement factory	6-8 tonne truck	45km	256 tkm
3	Windfarm to Landfill	6-8 tonne truck	120km	684 tkm

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.

4.2.2.6 Processing of Blade Waste

In Scenario 1, the 1.5 m^2 pieces are shredded into <40mm^2 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/hr 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 1.5m^2 pieces are be shredded into <40mm^2 size pieces using a shredder at the Irish pre-processing site. The processing capacity is estimated at 150kg/hr with a total specific energy demand of 0.17 MJ/kg, based on the Wittman ML2201 (Shuaib and Mativenga, 2016). In ecoinvent, the Irish low voltage energy mix was used in modelling 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, 2019b) 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.

4.2.3 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:

3. Robustness in assessing Global Warming Potential (GWP)
4. 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 or DALYs), Ecosystem Quality (Potentially Disappeared Fractions of species or PDF·m^2·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 normalised categories (Humbert et al., 2014). Normalised categories are unit-less, 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.

4.2.4 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 4.5.

Table 4.4 Variables included in the sensitivity analysis

	Expected Lower Impact	Chosen Value	Expected Higher Impact
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, 570kWp open ground installation, multi-Si | APOS, S	Electricity, low voltage {DE}| market for | APOS, S (German Electricity mix 2014)	N/A

4.3 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.

4.3.1 Comparison of Existing Disposal Methods

A comparison of the endpoint indicators of scenario 1 and scenario 3 show scenario 1 offers beneficial environmental gains due to the material substitution in all categories except Ecosystem Quality, and is overall less impactful to the environment than scenario 3 in all categories (Figure 4.4).

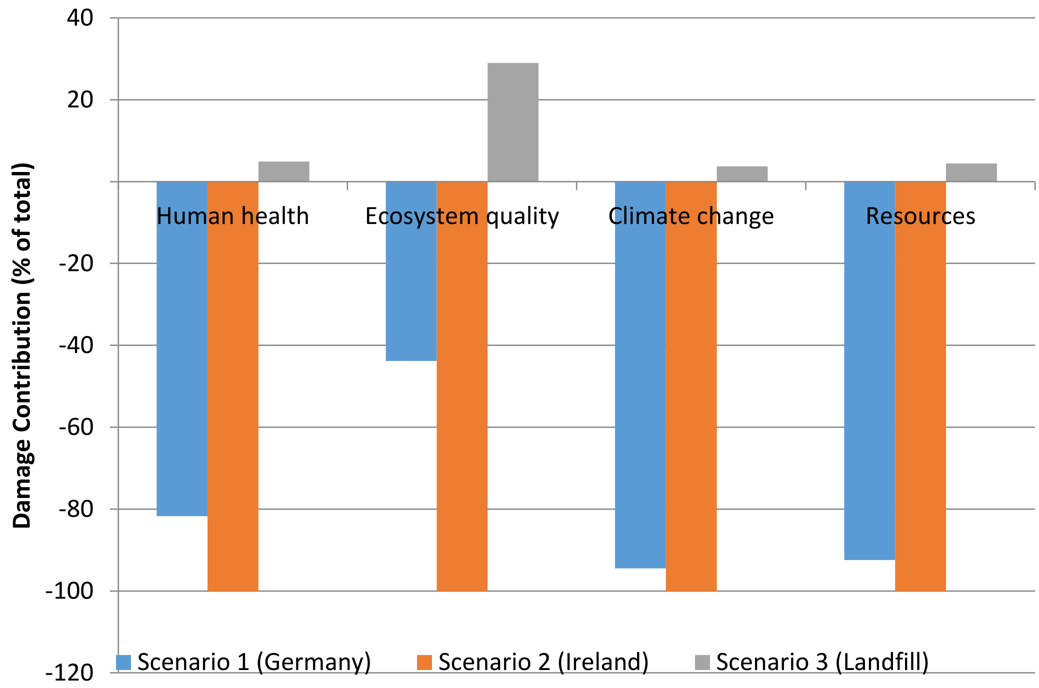

Figure 4.4 Damage assessment of scenarios 1, 2, and 3

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 (Figure 4.5). 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.

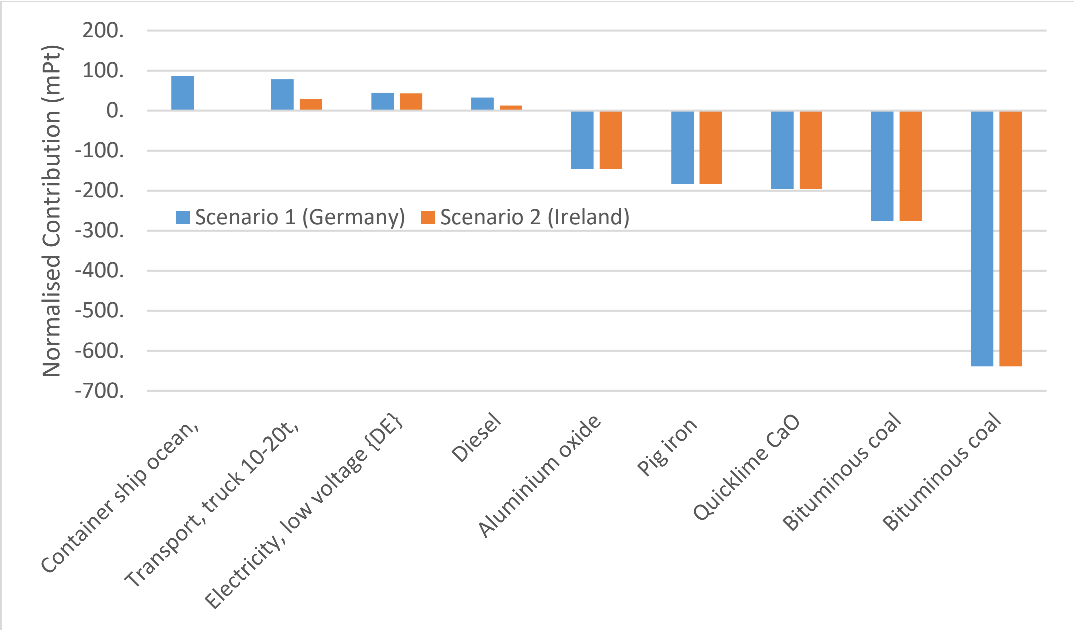

Figure 4.5 Scenario 1 and 3 process contributions to impact category Ecosystem Quality

4.3.2 Impacts of Theoretical Co-processing in Ireland

Scenario 2 is calculated to be the most environmentally beneficial in all damage categories as compared to scenario 1 and 3 (Fig. 4.6). 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. 4.4).

Using a single score output (Figure 4.6), scenario 2 is calculated as having the most negative, and therefore highest environmental benefit as compared to Scenarios 1. Although both scenarios are beneficial to the environment due to the modelling of material substitution, scenario 2 is calculated as 1.3 times more beneficial than scenario 1. Scenario 3 is calculated as having a positive single score assessment which indicates this scenario is environmentally damaging. Scenario 2 is approximately five times as beneficial to the environment as Scenario 3 is detrimental. 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.

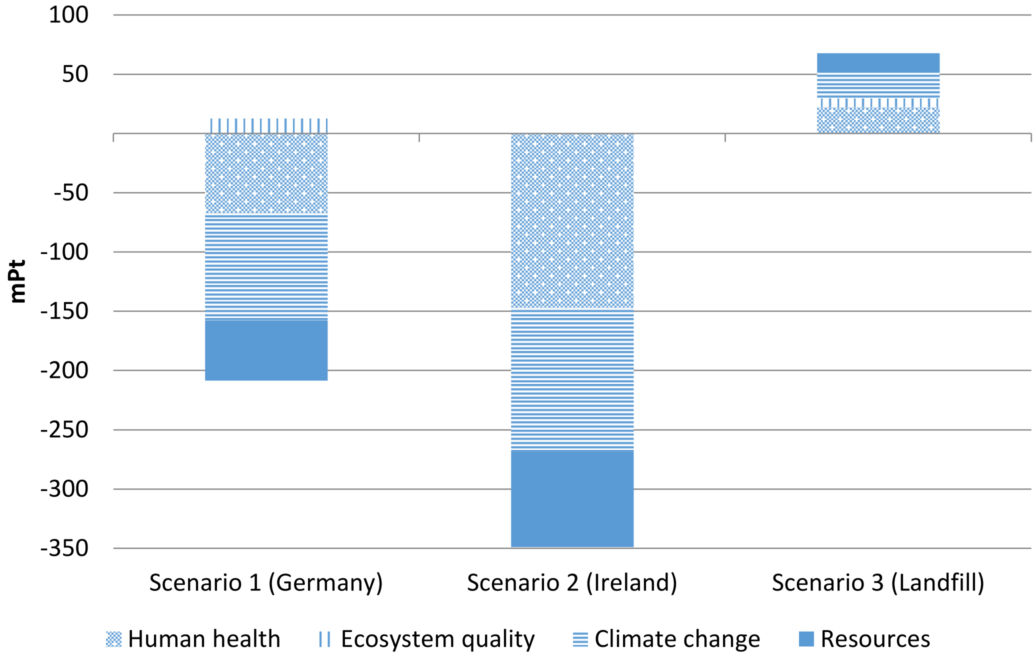

Figure 4.6 Single Score damage assessment comparing scenarios 1, 2, and 3

Figure 4.7 Impact Assessment per process for scenario 2

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 (Figure 4.7) and metal recycling. The negative impacts are due to the transportation and the shredding processes.

Table 4.5 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.

Table 4.5 Total Damage Assessment of Scenario 2

Damage Category	Material Substitution	Transport to SRF	V52 Blade Shredding	Transport Cement Factory	Total
Human health	-1.696	0.0089	0.0094	0.0046	-1.6731
Ecosyst quality	-0.087	0.0045	0.0016	0.0024	-0.0785
Climate change	-1.488	0.0072	0.0159	0.0037	-1.4612
Resources	-1.057	0.0067	0.0152	0.0035	-1.0316

4.3.3 Impacts of transportation versus substitution rates

4.3.4 Sensitivity Analysis

The results of the material substitution rate were discussed in section 4.3.3. A separate sensitivity analysis was run on the other process variables of transportation, shipment type, and electricity mix according to Table 4.5. A single score output is used to quantify the major effects due to varying the three inputs (see Appendix Table A.1, and 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 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.

4.4 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, and the first published paper to utilize LCA to quantify the environmental impacts of co-processing as compared to landfill for blade end-of-life disposal. 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 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 was found to be five times as beneficial as landfill in Ireland is detrimental, and 1.3 times better than co-processing in Germany.

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 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.

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.

5 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.

5.1 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.

5.1.1 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, 2020a). 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, 2020a). 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, 2020a). Of 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; Nagle et al., 2020). 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, 2020a). 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, 3 December 2020; Windtranz, personal communication, 10 December 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.

5.1.2 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., 2021b; 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, 2006b) 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.

5.1.3 Measuring Benefits

In construction, the GHG emissions of the lifecycle step 'Cradle to Gate' (A1-A3) is referred to as Embodied Carbon (Figure 5.1). 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 Figure 5.1) is also called Operational Carbon, which can be reduced through optimized design, 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.

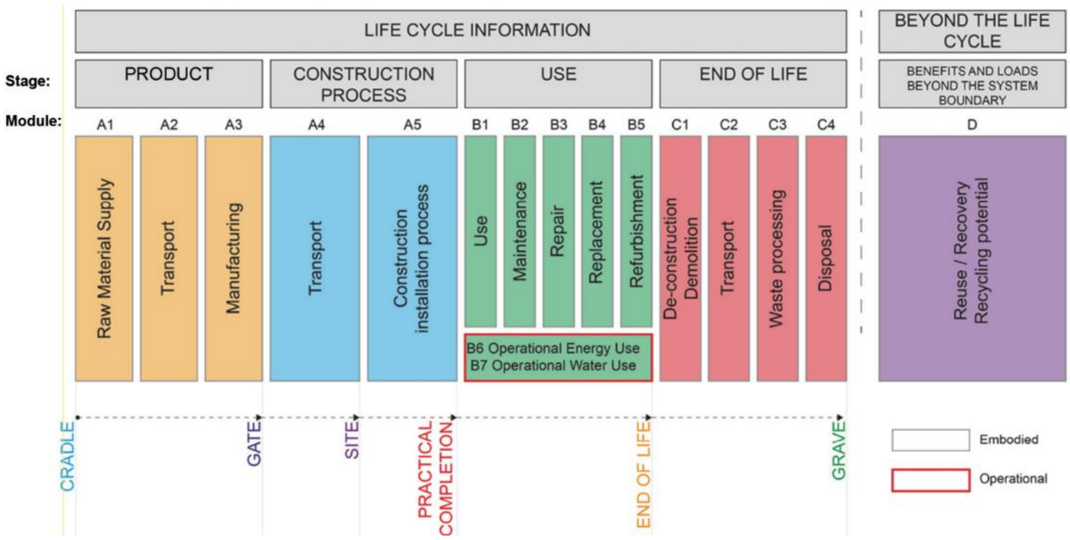


Figure 5.1 Life Cycle Stages in a Construction Project, per ISO 21931-2 (Gibbons and Orr, 2020)

The World Green Business Council's report entitled ‘Bringing Embodied Carbon Upfront’ addresses ways to reduce embodied carbon. Figure 5.2 shows that the vast majority of carbon reduction can be achieved through changes in the planning and design phases. Between 50%-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).

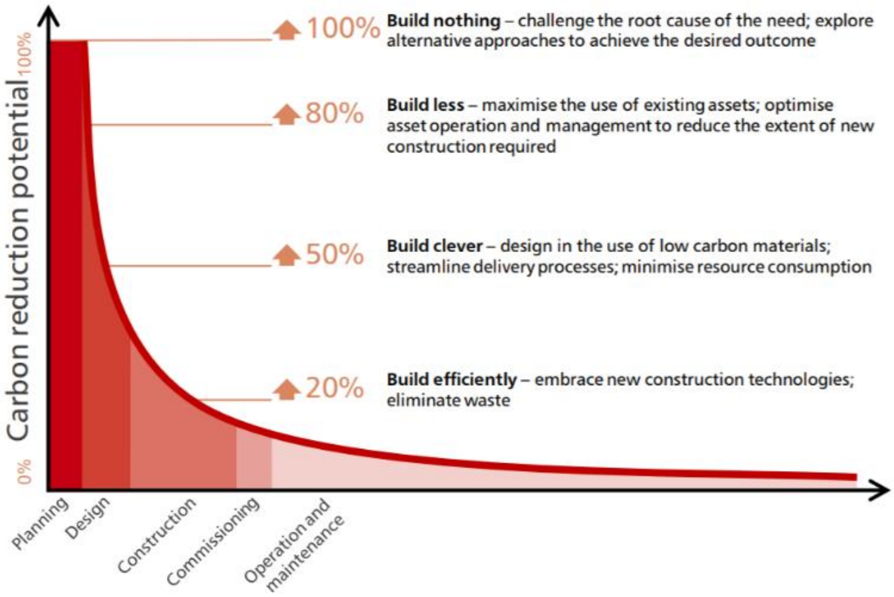


Figure 5.2 Carbon reduction potential at various stages of a project (World Green Building Council, 2019)

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 IStructE guide (Gibbons and Orr, 2020) includes CO_2 estimates for common and hard to abate construction materials (Table 5.1). Repurposing ideas can be quickly pre-screened for impact using this table, and the top impact ideas further explored, or assessed with a full LCA.

Table 5.1 Common construction materials and embodied CO_2/kg (Gibbons and Orr, 2020)

Construction Material	CO_2/kg
Concrete, non-structural	0.113
Steel (structural sections)	2.45
Timber (excl. carbon sequestration)	0.437 - 0.512

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 include consideration of public projects in order to capitalise on expected GPP requirements, as well as local applications. The specific research contributions are:

- 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.

5.2 Methods, Scenarios, and LCA

5.2.1 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., 2018b). 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 5.1: 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 Table A.2.

5.2.2 Scenarios

The Re-Wind group has generated a ‘dashboard’ of Geological Information System (GIS) data (see Figure 5.3), 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.

Figure 5.3 Dashboard depicting older Irish wind farms, developed by Queens University Belfast geography department in conjunction with the Re-Wind project (Delaney et al., 2021).

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 13-35 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 21.2m each (Figure 5.4). 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.

Figure 5.4 An example of a blade approximately 21m in length (photo credit Emma Delaney).

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 the 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.

5.2.2.1 *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 (Figure 5.5), 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, 13m middle sections, and 8m tip sections before transportation.

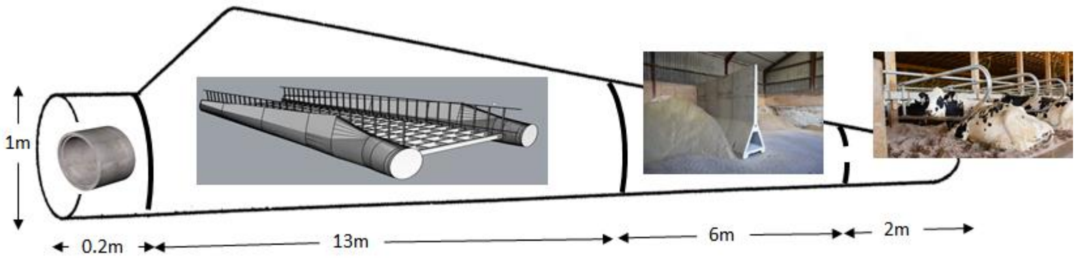


Figure 5.5 Scenario 1 usage for rural applications including a culvert, bridge, grain parition wall, and cattle partitions

Root section - Culverts or Manholes: The 0.2-metre root section of all 30 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-metre 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-metre sections will be done by 12-metre flatbed lorry with an allowed 1m 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 * 13m blades will replace galvanized steel U-beams manufactured and transported from the UK.

Tip section - Cattle and Grain Partitioning: The 8-metre tip sections can be cut and used as cattle partitions, and grain storage partitions. The last 2-metre tip section of the blades would be used as cattle partitions, replacing an amount of 76mm galvanised steel pipe. The remaining 6-metre 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.

5.2.2.2 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 2019-2025 (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, 12m middle sections, and 9m tip sections before transportation (Figure 5.6).

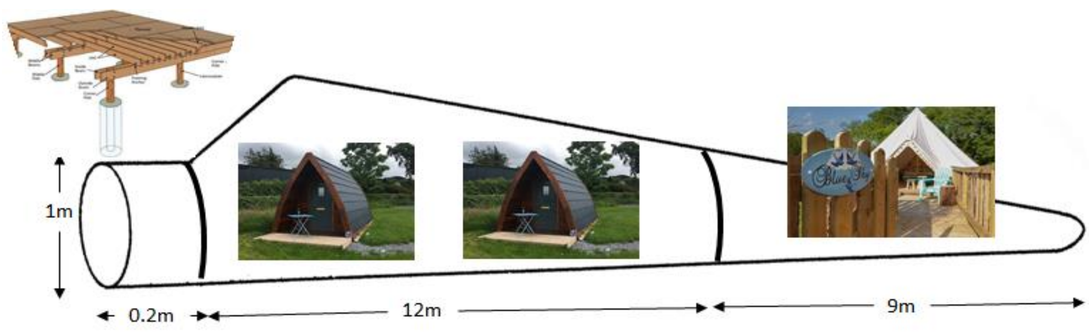


Figure 5.6 Scenario 2 for DIY enthusiasts to build glamping pods and barrier walls

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-metre lengths for transport, and then cut into two 6-metre length pieces upon arrival at the glamping site. The 6-metre sections would then be cut lengthwise in a fillet cut, bisecting the shear webs of the blade to serve as the roofing (see Figure 5.7). These sections would replace an amount of timber for the roof structure and coated sheet steel for water protection (Bank et al., 2019).

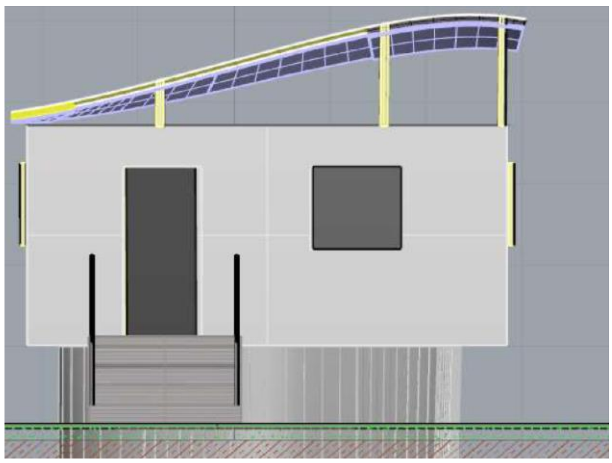


Figure 5.7 Blade with 'fillet' cut, used as roof section (Bank et al., 2019)

Tip section - Fencing: The final 8-metre 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.

5.2.2.3 Scenario 3: County Council Urban Package. Planters, Bus Stops/Bicycle Shelters, bollards

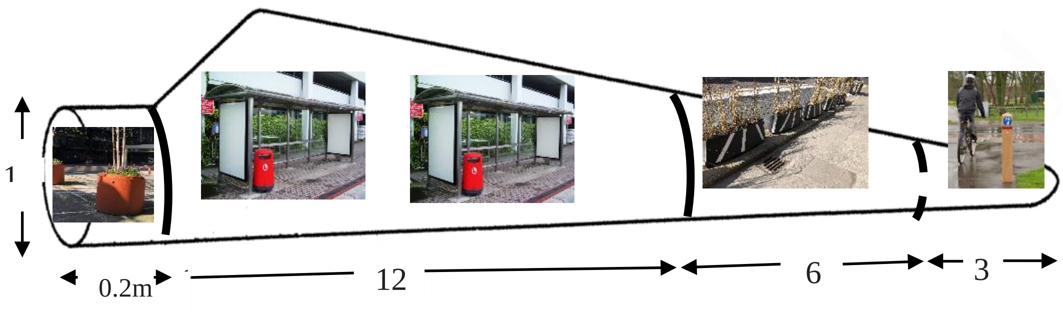


Figure 5.8 Scenario 3 rural application including planters, bus shelters and bollars

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 (Figure 5.8). 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, 12m middle sections, and 9m 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 12m 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 6m of the tip sections will be cut into 0.5-1m sections and made into oval-shaped planters, which will replace an amount of concrete. The final three metres of the tip will be cut into two 1.5m sections, and made into posts or bollards, replacing an amount of new GFRP material.

5.2.3 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 (Figure 5.9) 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 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 21.2m 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.

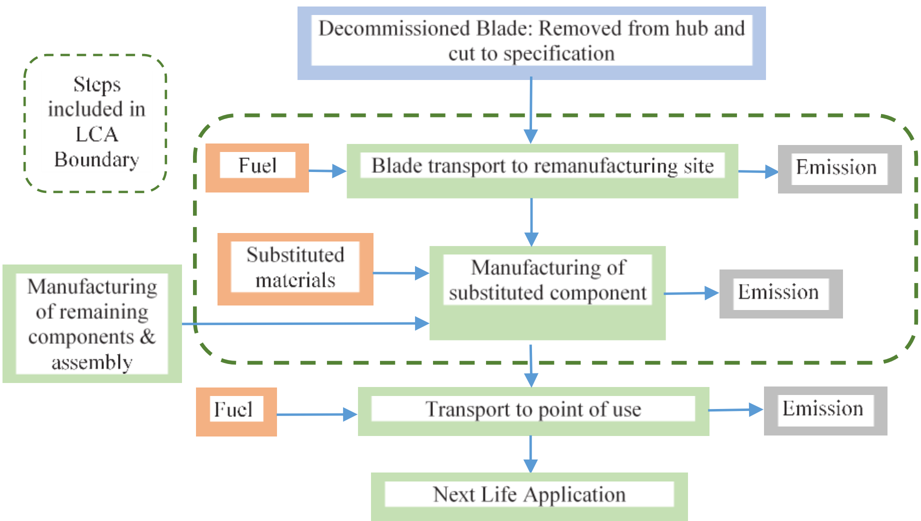


Figure 5.9 LCA Boundaries for scenarios 1, 2, and 3

The functional unit is: The utilization for 60 years of 30 * 22 metre 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 Sustainability, 2019a) 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). IMPACT2002+ 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.

5.2.4 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.

Table 5.2 Scenario 1 material quantity replacement calculations

Application	Blade Utilized	Material Substituted according to Functional Unit	Material calculations
Culverts	Root	Root section replaces 30 * 0.2m * 909mm OD pre-cast concrete pipe, 97mm wall thickness. Pre-cast concrete is 2.4 tonnes/m^3. 60 year lifespan.	7106 kg concrete
Bridge	Middle	Blades replace 203x133x25 galvanised UB girder. 13m * 30 blades * 25 kg/m (density of U-Beams). 60 year lifespan.	9750 kg galvanised steel
Cattle Partitions	Tip End	2 m tips replace 76mm OD galvanized steel cattle partitions: 30 blades * 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 6m long, 0.6m high, and 150mm thick, at 2.4 tonnes/m^3. Doubling up of blades would give 15 walls (rather than 30). 60 year lifespan.	19440 kg pre-stressed concrete

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 Table 5.2, Table 5.3, and Table 5.4.

Table 5.3 Scenario 2 material quantity replacement calculations

Application	Blade Utilized	Material Substituted according to Functional Unit	Material calculations
Small Housing - Piling	Root	Concrete foundations 1m diameter * 0.2m deep * 30. 60 year lifespan.	4.71 kg concrete
Small Housing - roofing	Middle	Wooden roof trusses: 30 blades * 2 pods/blade * 16 trusses/pod * 2.5m lengths * 4x2 inch beams (0.1m * 0.05m) * 2 lifetimes. Poly-coated sheet steel: 30 * 2 * 2.5m * 6m * 0.0006m * 2 lifetimes * 8039kg/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. 9m * average (1.088m-0.534m)*.016m thickness*30 pieces. 20 year lifespan No wood preservative required either, at 12kgs/m^3 * volume of wood 20 year lifespan.	10.5 m^3 wood 126 kg wood preservative

Table 5.4 Scenario 3 material quantity replacement calculations

Application	Blade Utilized	Material Substituted according to Functional Unit	Material calculations
Round Planters	Root	Root section replaces 30 * 0.2m * 909mm OD pre-cast concrete pipe, 97mm wall thickness. Pre-cast concrete is 2.4 tonnes/m^3. 60 year lifespan.	7106 kg concrete
Bus Shelters, Bike Racks	Middle	30 sections * 3 cuts * 1.5m wide * 4m bus shelter roofs made from polycarbonate. Bus shelter roof is curved: a roof with 1.5m depth results in an arc length of 1.7m. Assume 8mm polycarbonate thickness. Density 1.22 kg/m^3. Lifespan of 10 years.	35.8 kg polycarbonate
Oval Planters	Tip End	30 * 6m tip mid-section replaces oval shaped concrete planter perimeter 1.764m * 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 * 1.5m * .04m^2 posts. GFRP density estimated at 1.8 kg/m^3. 60 year lifespan.	6.48 kg GFRP

5.2.5 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 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, 2020a). Quantifying the impacts or benefits of recycling the GFRP blade product material is outside the scope of this paper.

5.2.6 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 (see Table 5.3) (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). 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 5.3: LCA Inputs for co-processing based on a functional unit of 45,000 kg of blade waste (Nagle et al., 2020).

Input Material and Processing	Raw Material Equivalent	% raw materials substituted	Raw material replaced & processing required
1000 kg blade waste	600 kg coal	600 kg/1000 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	5292 kg SiO_2
		5%Al_2O_3	1260 kg Al_2O_3
Steel Recycling	5% of blade is steel	N/A	2250 kg of steel
Shredding	0.17 MJ/kg	N/A	7650 MJ required for shredding

5.3 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 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 (Figure 5.10a), 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 (Figure 5.10.b), 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 (Figure 5.10.c), 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).

Figure 5.10.d compares all three scenarios and co-processing using the single score indicator, which is a normalised 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.

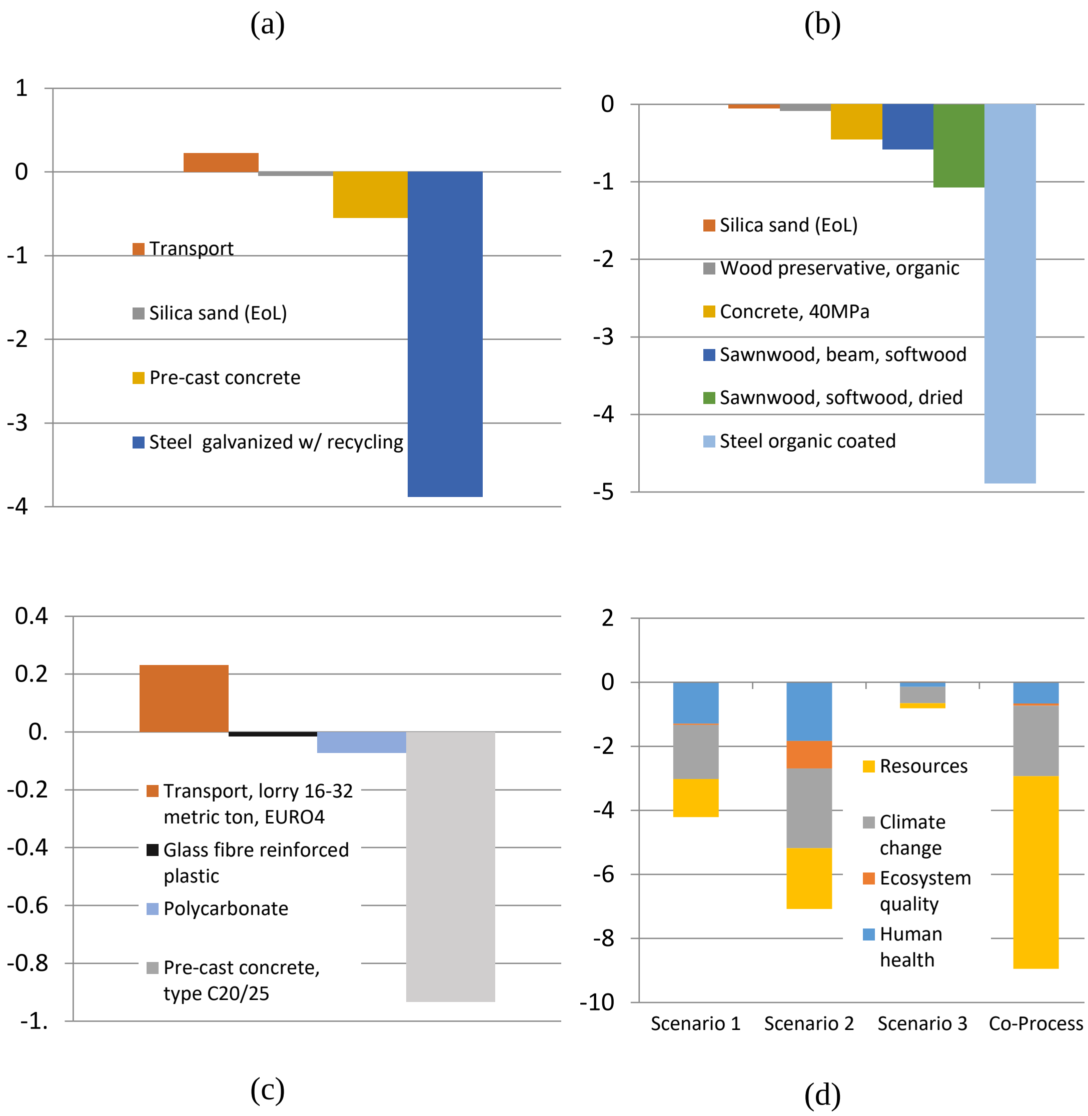


Figure 5.10 Process contributions per scenario: (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, and (d) Single score assessment of the three scenarios compared to co-processing. All y-axis units are in Points

Scenarios 1 and 3 included travels 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.

Table 5.4: 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, 40MPa	-617
Pre-cast concrete type C20/25	-2826
Steel hot dip galvanized, w/recycle	-4685
Steel organic coated/EU	-6845
Polycarbonate & GFRP	-328
Total of all processes	-15,300
Total kg CO_2/Functional Unit	-342 kg CO_2/tonne

Returning to the consideration of embodied carbon, we can calculate 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 reduction that can be achieved by substituting raw construction materials with a tonne of blade waste (Table 5.4).

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 3115 km driven in an average Irish vehicle (SEAI, 2018).

5.4 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 end-of-life 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 (Figure 5.11) (Joustra et al., 2020). 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, 2008b), 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.

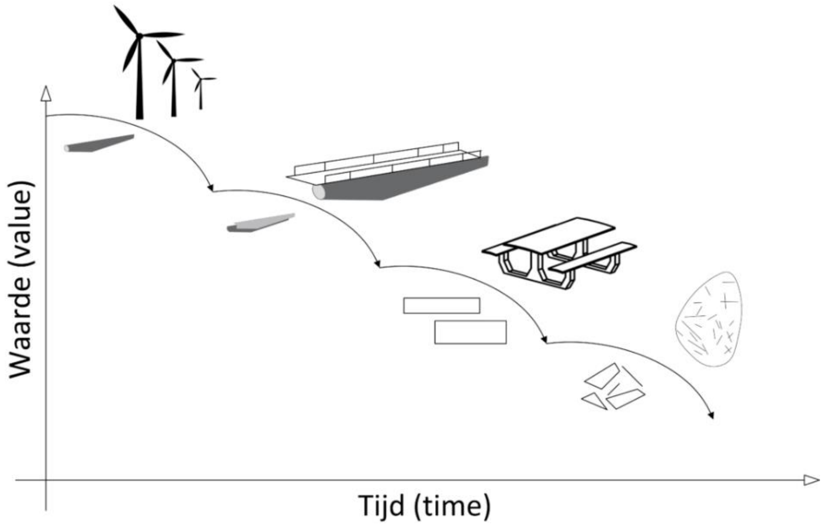


Figure 5.11 Time and value aspects of repurposing blades, illustrating the reducing value at each repurposing cycle, but the ability to keep the material in use longer (Joustra et al., 2020)

Other repurposing barriers include 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.

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 2023-2039, peaking at 370 turbines in 2037. This amounts to an average of 150 turbines or 450 blades per year, with lengths between 23m and 55m, increasing proportionately from 2023-2039. 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 5.5 is a calculation of the number of products that could be built with the average amount of blades available per year, as well as an estimated feasibility of utilizing the amount of blade material in each application, based on product research. If 100 tonnes of blade material were repurposed annually, or approximately 15% of the average yearly amount of unwanted blades in Ireland, then 23,000 kg CO_2 e emissions could be avoided per year

Table 5.5 Quantity of products required to utilize average annual blade waste amounts in Ireland from 2023-2039

Application (and part of blade used)	Use of 450 blades between 3 scenarios	Estimation of feasibility of each application per year
Culverts (root)	75m of culverts	Fully Feasible
Bridge (mid)	75 bridges	Would require 225 km of greenways/year. 30% feasible
Cattle Partitions (tip)	150 partitions	At 70 head of cattle per farm, this would outfit 2 farms. Fully feasible
Grain partition walls (tip)	75 grain partition walls	30% feasible
Small Housing – Piling (root)	37 pilings	Would require 9 tiny homes. Fully feasible
Small Housing – roofing (mid)	300 glamping roofs	10% feasible
Fencing & perimeter walls (tip)	1350 0.2 * 1 m fence pieces	50% feasible
Commodity Items – Planters (root)	150 one metre high planters	20% feasible
Bus Shelters, bike shelter (mid)	450 bus or bike shelters	10% feasible
Commodity Items – Planters (tip)	900 one metre high planters	10% feasible
Signage (tip)	300 bollards	20% feasible

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 5.5, 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 a waste diversion declaration 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.

5.5 Conclusions

This chapter presents the first known LCA quantifying the impacts of repurposing blade material for civic and private structures. These impacts are compared against the baseline disposal method developed in Chapter 4 of co-processing in a cement kiln, to offer a rigorous assessment of repurposing from a waste disposition perspective. It offers an estimated amount of carbon emissions that could be diverted per tonne of blade material that is repurposed, which will be a useful metric for blade repurposing companies who are planning to bid on publicly tendered works with green public procurement requirements.

The key findings in this chapter 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 costs 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 declaration for wind farm owners who choose to repurpose their decommissioned blades. Finally, more work should be done on the implications on rural job creation and improved supply chain resiliency through the repurposing of waste material.

6 Life Cycle and Cost Assessment of a Pedestrian Bridge made from Repurposed Wind Turbine Blades

6.1 Introduction

6.1.1 Irish & EU Policy

The European Green Deal lays out a plan for Europe in which economic growth is decoupled from resource use, with zero net emissions of greenhouse gases by 2050 (European Commission, 2019). An increase in renewable energy across Europe is central to the Green Deal's goal of zero emissions by 2050, and continued development of wind energy is key to this. However, as wind energy capacity grows and older wind farms reach end-of-life, sustainable disposal options are needed for decommissioned turbine parts, in order to prevent 'green energy' from becoming a significant generator of waste.

6.1.2 Blade End-of-life Problem

Composite wind blades, which have proven to be the 'sustainability blind spot' of the wind energy industry (Sakellariou, 2018), are particularly challenging to deal with at end-of-life, which in and of itself is difficult to define (Bank et al., 2021)). Blades made from glass fibre reinforced polymer (GFRP) often end up in landfill, incineration (Cousins et al., 2019; Rahimizadeh et al., 2019), or co-processed in a cement kiln (Albers, H., Greiner, S., Seifert, H. and Kuehne, 2009; European Composites Industry Association, 2013; Nagle et al., 2020; Sakellariou, 2018; Schmidl and Hinrichs, 2010). Incineration, which leaves over 50% of the blade as ash, is no higher on the EU waste hierarchy than landfill (European Commission, 2008a). Recycling options are available but not economical due to high cost or poor quality of recovered materials (Jensen and Skelton, 2018; Oliveux et al., 2015; Rybicka et al., 2016; WindEurope, 2020a). None of these options exploit the residual mechanical properties of the GFRP. Landfill of bulky composites in Europe will decrease as gate fees increase, or it will be banned outright as in Germany, Austria, Finland and The Netherlands (WindEurope, 2020a). Wind Europe is now calling for a European wide ban on landfilling of blade material by 2025 (WindEurope, 2020b).

Wind turbines have a design life of 20 years (Bank et al., 2021), but may be able to perform up to 30 years or more, as has been seen in the Bellacorick Wind Farm on the west coast of Ireland, installed in 1992 (Bord na Mona, 2021). Turbines are decommissioned for many reasons, which may be from financial incentives or disincentives rather than equipment performance (Gentry et al., 2020), and blades can potentially be in sound condition upon decommissioning. Initial studies show that blades stressed to their design life limits have nearly the same properties as new blades (Beauson and Brøndsted, 2016). Thus, decommissioned wind blades may perform well in another use, under low stresses where durability is the main concern (Alshannaq et al., 2021b). Capitalizing on the residual properties by re-purposing the blades into large structures has the potential to be less environmentally impactful than recycling or co-processing. Several studies showed promising results in modelling the use of decommissioned blades in roofing (Bank et al., 2019; Gentry et al., 2020), electrical transmission towers (Al-Haddad et al., 2022; Alshannaq et al., 2021b) and short span pedestrian bridges (Jensen and Skelton, 2018; Ruane et al., 2022; Suhail et al., 2019). In fact, the main shortcoming with utilizing blade waste in these applications is that these options might be difficult to scale up in order to consume the amount of waste that is expected (WindEurope, 2020a).

6.1.3 The Pedestrian BladeBridge

The pedestrian BladeBridge, designed by researchers in the Re-Wind Network (www.re-wind.info, (Ruane et al., 2022; Suhail et al., 2019) was recently constructed as part of a new greenway project in County Cork, Ireland (Stone, 2022). The BladeBridge used decommissioned wind turbine blades as the bridge superstructure, thereby replacing an amount of raw material that would have been required in a typical bridge build. Technical feasibility was demonstrated through reverse engineering and load testing of the blades, detailed in a previous project paper (Ruane et al., 2022). In-situ renderings of the BladeBridge, as well as renderings of alternate bridge designs are included in the 2021 Re-Wind Fall catalogue (McDonald et al., 2021).

The repurposing of materials in construction projects, despite being clearly beneficial environmentally and economically, is fraught with difficulties. To offer a brief definition of terms, 'reuse' requires a material to be used in a similar application, while 'repurposing' is defined as the use of a material in a different application. In the case of decommissioned wind turbine blades, 'reuse' would mean the blades are used again as wind blades, while 'repurposing' would mean the blades are used whole or in sections in a different application such as a bridge girder (Gentry et al., 2020). Some of the barriers to repurposing of construction material include quality concerns regarding previously used material, possible contamination, unpredictable material availability, negative perceptions, and insurance and liability (Jensen and Skelton, 2018; Shooshtarian et al., 2020; Williams, 2020), any of which could introduce intolerable risk to a project. More specifically, barriers for using decommissioned blades in the construction of a pedestrian bridge were identified by Jensen & Skelton as (a) economics, (b) testing expertise, (c) cutting of the blade to design, (d) transport of the blade, and (e) bridge foundation design (Jensen and Skelton, 2018). Adding to these barriers is the reluctance of blade manufacturers to release blade designs, thus requiring extensive reverse engineering of each model of blade before repurposing solutions can be developed (Alshannaq et al., 2021a; Ruane et al., 2022). This reverse engineering is costly in engineering time, and environmentally impactful due to the energy demands of the equipment and consumption of materials.

Negative perceptions of reuse or repurposing could be changed by showcasing reuse and repurposing through high profile projects or visible civic works that are positively viewed by the local community. Bringing the idea of a circular economy, which is defined as 'a framework for an economy that is restorative and regenerative by design', is essential in changing the perception of repurposing. In the words of Ellen MacArthur '*Setting up exemplar projects in strategic places in the city can be an inspiring way to demonstrate what is practically possible and demonstrate the opportunities that a circular economy can bring to a city'* (Ellen MacArthur Foundation, 2019). In line with this thinking, this paper presents a case study which demonstrates how Ireland might embrace repurposing and the circular economy, by building the pedestrian bridge in a visible location along a cycleway that is anticipated to be a national and international attraction (Cork County Council, 2019).

The BladeBridge project supports several Irish goals aligned with the EU Green Deal including following green public procurement (GPP), which encourages reuse and repurposing of materials in government projects (European Commission, 2019). Ireland is also working to improve its performance on Sustainable Development Goal (SDG) 12 - Sustainable Consumption and Production, which is based partly on circular material use (Clark et al., 2020), in which Ireland is 2nd last out of all 28 EU countries at 1.6% (Eurostat, 2018). The Irish program for government includes a pledge to spend the equivalent of €1 million euros/day on cycling and walking infrastructure, and develop an integrated national network of greenways across the country (DTTAS, 2018; Leahy et al., 2021). Between the need to improve on SDG12 through circular material use, the push to build cycling infrastructure across the country

(DTTAS, 2018), and the availability of decommissioned blade material (Delaney et al., 2021), an opportunity exists in Ireland to use repurposed blades in the construction of bridges on cycle ways .

6.1.4 Life Cycle Thinking in Bridges

To support GPP efforts and the improvement of performance towards achieving SDG 12, repurposing blades as girders for pedestrian bridges must perform better environmentally than both the current blade disposal method and the use of conventional materials to build a bridge, and at an acceptable cost. Life cycle assessment (LCA) can be used to perform a comparative environmental analysis, such as this. LCA is a well-established tool in which all inflows and outflows are compiled across the full life cycle of a process or system, and environmental impacts are quantified and evaluated (ISO, 2006b). Life cycle costing (LCC) is another tool that can help to evaluate the use of repurposed material in the construction sector. LCC refers to the present value of the total cost of a product or service across the full lifespan of a product or process (Swarr et al., 2011). LCA and LCC are becoming increasingly important in civil engineering projects like bridges, as can be seen in the increase in standards on this subject recently (Ek et al., 2020b). ISO 21931-2(2019) provides a framework for combining LCA and LCC into an assessment of the sustainability performance of civil engineering works (ISO, 2019), which breaks lifetime phases into more granular modules. The lifetime phases are indicated by the letters A, B, C, and D and numbers are appended to indicate the sub-phases within each phase. Modules A0 include design and preconstruction activities, A1-A5 is Production and Construction, B1-B8 is Use, C1-C4 is End-of-life, and D includes future loads and benefits such as recycling or repurposing of materials. See Figure 6.1.

While ISO 21931-2(2019) is titled ‘A framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment’, the social indicators included are simply the LCA Human Health indicators (ISO, 2019) rather than social indicators suggested by the UNEP Social LCA Guidelines (Benoît Norris et al., 2020). A social-LCA framework will be detailed and utilized in the next two chapters. This chapter will focus on the environmental and economic performance only.

The majority of sustainability assessments on pedestrian bridges indicate that the highest cost and environmental impact is due to the materials used in the production phase (A1-A3)

(Cadenazzi et al., 2020; Du et al., 2014; Ek et al., 2020a; Mara et al., 2013b; Niu and Fink, 2019; Penadés-Plà et al., 2017). LCA/LCC is most impactful when applied at the design phase (A0) (Coenen et al., 2021; Ek et al., 2020b; Penadés-Plà et al., 2018), therefore, the material choices selected at this phase, such as selecting repurposed material, should offer the most impact in phases A1-A3, and across the project lifecycle.

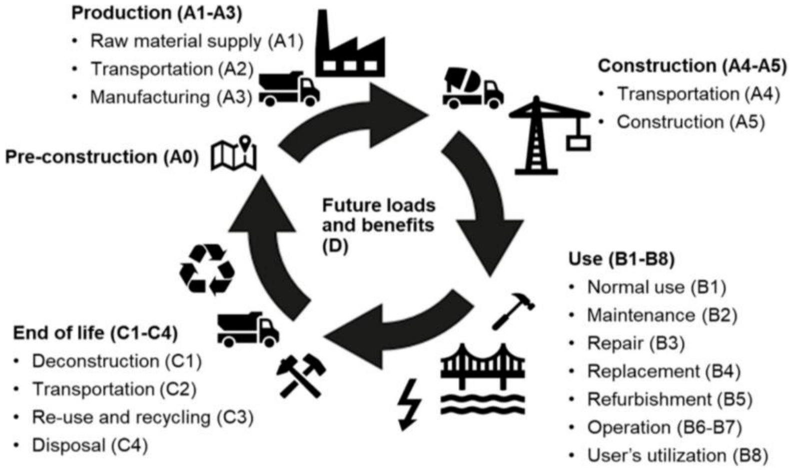


Figure 6.1 Life cycle phases of an infrastructure project (Ek et al., 2020a)

The construction and maintenance phases are the next most impactful in the lifecycle of a bridge (Niu and Fink, 2019). The construction phase includes energy use and emissions from on-site machinery such as cranes, and can be diminished by the utilization of lighter construction materials such as GFRP (Ilg et al., 2016). Maintenance impacts can be calculated by developing scenarios for phase B1-B8, based on maintenance schedules for existing similar bridges in the same region (Ek et al., 2020b; Niu and Fink, 2019). Note that with pedestrian bridges, the impact due to Use (B1) does not have to be included as use of a pedestrian bridge typically does not generate emissions (unlike a vehicular bridge in which emissions from the vehicles are included). The end-of-life phase (C1-C4) tends to be regarded as the least impactful, or in some cases beneficial due to recycling of steel or crushing and theoretical carbonating of concrete (Penadés-Plà et al., 2017). However, recycling of steel or modelling the carbonation of concrete will look very different in 60-120 years, and thus, modelling the use of the bridge components in this timeframe may be too uncertain to be useful. In the absence of this, designing the bridge to be easily dismantled, adapted or transformed may help to widen the end-of-life options in an uncertain future (Coenen et al., 2021).

6.1.5 LCA/LCC of FRP in Bridges

GFRP is a high performance material used not only in wind turbines, but less frequently in infrastructure applications such as bridges (Bank, 2006)). High performance materials, which also include high-performance concrete and fibre-reinforced concrete, can be 10% more expensive than standard steel reinforced concrete, but require less maintenance, and are lighter and more durable (Ilg et al., 2016). A summary of multiple bridges with GFRP decks in the USA showed that when LCC was applied, the total life cycle cost estimate was 8.4% lower than standard materials (Ilg et al., 2016). An LCA/LCC study comparing the rehabilitation of a bridge deck with conventional steel-concrete versus GFRP showed the GFRP deck as more favourable overall. While the manufacturing of GFRP released more CO_2 than the conventional materials, the impacts due to transport and the abutment material quantity were reduced due to the lighter weight of the GFRP material, resulting in overall lower costs and emissions (Mara et al., 2013a). The lightweight GFRP material also allows for faster bridge erection, resulting in less disruption in traffic, a social metric which should be taken into account (Mara et al., 2013a). A contradicting study showed that the LCA of a GFRP deck was slightly worse than an steel/concrete deck, when results were normalised and combined across all categories (Mara et al., 2013b), due to the GFRP manufacturing impacts. These studies show that high performance materials can be cheaper across the lifecycle of an infrastructure project due to being lightweight, durable and low maintenance, but a LCC approach would need to be used in the tendering process in order to capture the overall benefits. The contradicting studies indicate that newly manufactured GFRP is likely only slightly better from an environmental standpoint when compared to steel or concrete, due to the impacts of manufacturing of the material. This further supports the idea that the use of repurposed GFRP material would offer gains on both fronts: the project would benefit from the durability and lightweight nature of a high performance material without the high cost of procurement, and with none of the environmental impacts of the manufacturing or the importing of materials.

6.1.6 Circular Economy and Life Cycle Assessment

Although LCA is a well-established tool for quantifying lifetime impacts of a process or product, it lacks the ability to include all aspects of circular design. LCA was originally designed as a linear 'cradle to grave' assessment, with the assumption that all products or processes would reach an end-of-life (Stanchev et al., 2020). LCA does not account for design issues, such as design for disassembly. It also does not take into account larger, economy-wide factors such as the incorporation of materials that have an established supply chain for reuse, repurposing or recycling (Peña et al., 2020), or the utilization of materials from ‘anthropogenic deposits’ such as waste material (Sonderegger et al., 2020). Several studies have shown that the most circular option is not necessarily the most environmentally preferable option (Haupt and Zschokke, 2017; Lonca et al., 2018). A review of eight studies which included both LCA and circular assessments concluded that LCA could be enriched by the inclusion of an evaluation of the circularity of a system, but that CE indicators should be both separate and subordinate to LCA (Rigamonti and Mancini, 2021).

Many bridges are demolished due to changing functional demands rather than structural or material deficiencies, and future uncertainties due to climate change will only exacerbate this (Coenen et al., 2021). A bridge-specific circularity assessment framework was developed recently. The framework is based on the four stages of an LCA, with the goal and scope definition remaining the same, and the life cycle impact assessment replaced with the ‘bridge circularly indicator’ (Coenen et al., 2021). This framework considers not only material flows, but also the ability for the bridge to be adapted during its lifetime or its components to be reused at end-of-life, based on the original design.

The research contributions of this chapter are:

1. First LCA and LCC conducted on a pedestrian bridge built using decommissioned wind turbine blades, as compared to a bridge built with conventional materials.
2. First LCA and LCC conducted on the end-of-life use of decommissioned blades in a pedestrian bridge, as compared to baseline disposal method of co-processing the amount of blades in a cement kiln.
3. The first circularity assessment of a bridge built with decommissioned blades.
4. Discussion of a BladeBridge business model in Ireland

6.2 Methodology

6.2.1 BladeBridge (Case Study)

The Midleton to Youghal greenway is a 23km cycleway in the south of Ireland, near Cork City (McConnell, 2021). Cork County Council is managing the project, and chose to locate the BladeBridge at a stream crossing 2 km from the start of the greenway at the Midleton train station (Figure 6.2). The county council was interested in publicly displaying their efforts at material repurposing, and thereby chose the location for maximum exposure to users.

Figure 6.2 The BladeBridge installation near the Midleton train station in Cork, Ireland, under construction late January, 2022 (source Author)

The blades were sourced from an onshore wind turbine asset management company, Everun (www.everun.ltd), in Belfast, Northern Ireland, United Kingdom, who had an assortment of blades from decommissioned farms in Northern Ireland. Blades from a Nordex N29 turbine manufactured by LM Glasfiber A/S in Denmark and known as the LM 13.4m blade (Hahn et al., 2016), were chosen, as the 13.4m length was the most similar in length to the initial study conducted within the Re-Wind project for a Vestas V27 wind blade (Suhail et al., 2019). Three blades at 0.75 tonnes each were transported – two for the girders and one for structural testing. Blades were shipped 430 km from Belfast to Cork, and delivered to the Civil Engineering test lab at Munster Technological University (MTU). BladeBridge testing and design was done in collaboration with the extended Re-Wind Network (Re-Wind Network, 2021), the MTU lab technicians and the Civil Engineering supervisor, who is a chartered Civil and Structural Engineer. Fabrication was performed by a local steel fabricator.

6.2.2 Life Cycle Assessment and Life Cycle Costing Overview

To support efforts to improve performance against SDG 12, repurposing blades as girders for pedestrian bridges must perform better environmentally than the use of conventional materials. To assess the BladeBridge sustainability performance, a LCA/LCC is performed following the framework in ISO 21931-2 (ISO, 2019). An overview of the case study is first detailed (Table 6.1). LCA has 4 Steps: (1) Goal and Scope definition, (2) Inventory, (3) Impact Assessment and (4) Interpretation (ISO, 2006b). The LCC will follow the same framework, but phase (3) will consider lifecycle cost information rather than impact assessment.

Table 6.1 Case Study Specific prerequisites for the assessment

Characteristic	Case Study Prerequisite
Object of Assessment	4m * 5.5m pedestrian bridge, situated 2 km from Midleton train station on the Midleton to Youghal greenway
Intended Use of Study	Comparison between the uses of decommissioned GFRP wind blades in a one-off bridge construction, to scaled data of a recently built bridge with a steel superstructure, supplemented by standardised Irish infrastructure cost data (Transport Infrastructure Ireland, 2019a)
Additional Functions Provided	None
Functional Equivalent: (a) Type/use of the civil engineering works, (b) Capacity, c) Reference study period and pattern of use (d) Design life	(a) Pedestrian/cycleway bridge (b) 5.5m span, 4m width rated to take emergency vehicles on occasion (c) See Scenario description d) 60 year design life
When was assessment performed	Design & Construction Phase

Life Cycle Stages Assessed	A0-5, B2-5, Qualitative discussion of C1-4, and D
Justification of exclusion of modules	B1 (Normal Use) of a pedestrian bridge generally contributes no emissions, B6-7 (Operations) not applicable to bridges. C1-4, and D are too far in the future to perform meaningful estimates, and a discussion around design to broaden end-of-life options is offered instead
Area of Influence	Environmental and economic dimensions quantify; (regional social dimensions qualified in chapter 8)
Energy and Mass flow considered in assessment	See Appendix Tables A.3 and A.4
General assumptions and scenarios used	See scenario description section A.4 and LCI section
Sources of Data for the indicators	Methodology Section
Statement about whether data are specific or generic	Methodology Section
Reference Year for Cost Data	2022

6.2.3 Goal and Scope Definition

The goal of this study is to compare the environmental and cost impacts of a pedestrian bridge made using decommissioned wind turbine blades as girders against a bridge made with conventional materials. A temporal boundary of 60 years was chosen based on the engineering design of the BladeBridge, combined with guidance on the design working life of a bridge with primary load carrying structure of GFRP, in the UK (CIRIA C779, 2018). An attributional

LCA will be conducted on the full lifecycle of both the BladeBridge and the conventional bridge, and a comparative assessment then completed between the two cases.

The two separate environmental comparisons were completed, with two differing functional units: The functional unit for the bridge comparison study is ‘A 22m^2 pedestrian bridge with emergency vehicle load capacity of 12 tonnes, over 60 years.’

From a consequential perspective, the environmental impacts due to not landfilling the blades as well as the impacts of not processing the blades into cement clinker will also be assessed, based on a method developed in chapter four (Nagle et al., 2020). The functional unit of this assessment will be ‘The disposal of 3 * 0.75 tonnes of blade waste for 60 years’, based on the number and weight of the blades used for testing and constructing of the BladeBridge.

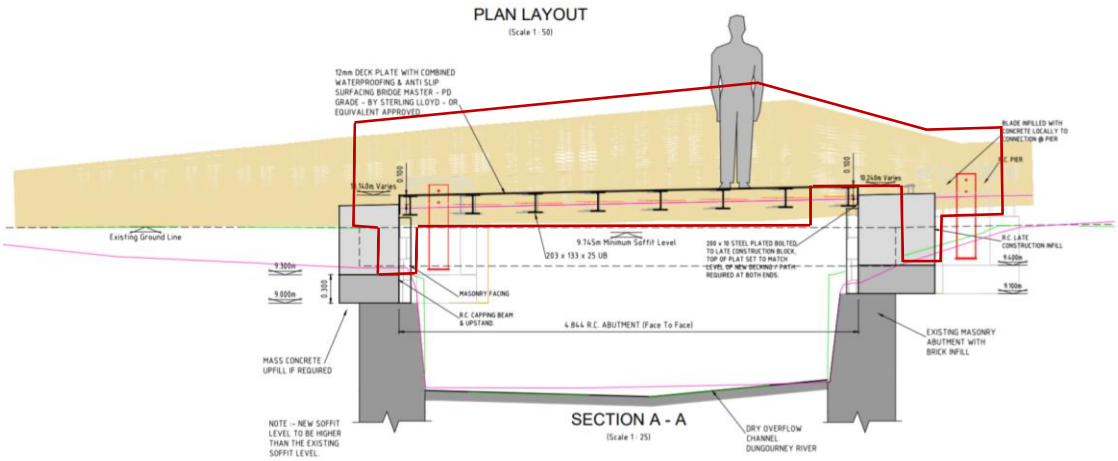


Figure 6.3 Physical boundaries include blade, cradles, superstructure, and decking (Image generated by Kieran Ruane, MTU)

Boundaries include reverse engineering on the third blade, steel material and manufacturing, transport of steel and blades to fabrication site, BladeBridge specific abutment work including steel cradles, formwork and concrete, parapets and lifetime maintenance schedule (Figure 6.3). The boundaries did not include site clearance, abutment formwork and concrete, transportation from fabrication location to installation site, crane hire, or final deck finish. All of these items were equivalent between both bridges and can be considered outside of the scope of the bridge design, structure, and BladeBridge specific supporting structure.

6.2.4 Inventory Analysis

Life Cycle Inventory (LCI) data collection followed ISO 21931-2 (ISO, 2019) stages A0-D. Scenarios were generated for each phase through interviews with the designer, contractors, and the customer (Cork County Council), and by referencing bridge LCA studies (Ek et al., 2020a). Costs, material quantities, and full details of the scenarios are in Appendix Tables A.3 and A.4. An overview of the approach to the data collection follows.

6.2.4.1 Pre-Construction (A0)

Design of the BladeBridge required extensive reverse engineering, most of which was destructive testing of the third blade including high temperature specimen testing. The energy consumed during this testing is included in the LCI, and cost of labour is included in the LCC.

6.2.4.2 Manufacturing (A1-A3)

Transport of the blades to the manufacturing site, and all materials consumed during the BladeBridge manufacturing are included in the LCI and LCC, including any blade repairs required. A recently constructed conventional bridge with a 44m span was used as the reference bridge, with the bill of quantities and costs scaled to $22m^2$. The parapets for the BladeBridge will require 50% of the material of a conventional bridge, due to the blade itself serving as a sidewall. The top of the BladeBridge parapet will stand at 1.4m high, as required for cycleway bridges, but will terminate at the trailing edge of the blade (see Figure 6.4). The parapet material required for the 5.5m length of the bridge will only be included. The remaining parapet material has not been included in the LCI or LCC as it was a cosmetic decision by the customer to extend the rail the length of the blades, and is not required for functionality or safety reasons.

6.2.4.3 Construction (A4-A5)

BladeBridge installation equipment and use time was supplied by the installation contractor, and a theoretical installation scenario for the conventional bridge was detailed as well. In the case of this bridge length, it was determined that the same size crane would be used for the BladeBridge installation as would have been used for a conventional bridge. Therefore, impacts due to the transport to site and crane use were omitted. Details of the BladeBridge specific concrete and formwork quantities were obtained from the BladeBridge drawings. Other works such as site clearance and clean-up of the existing abutments were also not included in the boundaries.

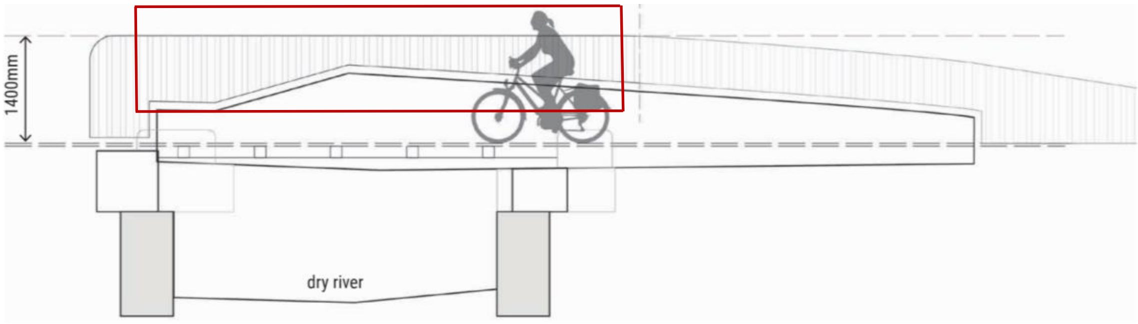


Figure 6.4 BladeBridge parapet detail showing reduced handrail material required (Image generated by The Paul Hogarth Company, commissioned by the Cork County Council)

6.2.4.4 Use/Maintenance (B2-B5)

Maintenance scenarios for the BladeBridge were generated from recommendations from the Composites UK handbook on FRP Bridges (CIRIA C779, 2018) and from the customer (Cork County Council) planned maintenance schedule for this bridge. The maintenance schedule for the conventional bridge was taken from a database of standard bridge maintenance schedules from the Irish transportation infrastructure body (DTTAS, 2018).

6.2.4.5 End-of-life (C1-C4)

The design life for this bridge is 60 years, and estimating the end-of-life use of the materials is too uncertain to be useful (Coenen et al., 2021). In lieu of quantifying end-of-life stages C1-C4 and Future Loads and Benefits stage D, a qualitative discussion of the circular aspects of the BladeBridge project will be included, based on a bridge circularity assessment framework (Coenen et al., 2021).

6.2.5 Impact Assessment

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. IMPACT 2002+ was selected for this assessment (Humbert et al., 2014), as it matches the impact assessment used in the author's previous research on blade recovery and repurposing (Nagle et al., 2022, 2020), and thus allows for direct comparison. Endpoint indicators, called Damage Categories, are used in this study. These indicators were discussed in depth in chapter four. They include Human Health (Disability Adjusted Life Years of DALYs), Ecosystem Quality (Potentially Disappeared Fractions or PDF*m^2*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. Normalized categories are unit-less, 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 (Humbert et al., 2014). SimaPro software version 9.1.07 (PRé Sustainability, 2019b) was used for this study.

6.2.6 Bridge Circularity Assessment

As discussed above, the design life for this bridge makes estimating the end-of-life of the materials too uncertain to be useful (Coenen et al., 2021). A qualitative discussion of the circular aspects of the BladeBridge project will be included instead, based on the following bridge circularity indicators (Coenen et al., 2021):

- Design Input: Recycled material, reused material, recyclable material, and overdesign
- Resource Availability: How scarce are the specified materials?
- Adaptability: Can the crossing or underpass be broadened, can the bridge be strengthened, and can the clearance be increased?
- Reusability: Disassemblability into components, transportability of components, uniqueness of components

6.2.7 Extrapolating to the 2nd – nth Bridge

Having gone through the process of developing the first BladeBridge product in Ireland, a review of the steps involved is performed to offer insight into the refinement of future BladeBridge production. Phases A0-A5 are revised and process inputs removed that were required for the testing and manufacturing of the prototype, but would not be required in subsequent bridges. Lessons learned from the first BladeBridge are also incorporated into these revisions. An LCA/LCC is then run on the modified design and phase inputs, assuming equivalent phase B. Analysing and reflecting on the choices made and the results achieved allows incremental improvements to the design choices and the removal of additional materials from over-engineering.

6.3 Data

Two separate environmental comparisons were completed, with two differing functional units. The first assessment compares the impacts associated with the lifetime of a pedestrian bridge, made with conventional materials or with blade material. The functional unit for this assessment is:

1. A $22m^2$ pedestrian bridge with emergency vehicle load capacity of 12 tonnes, over 60 years

The second assessment compares the impacts, or more appropriately, the gains, that can be achieved by the using the blades to substitute raw materials in two alternate end-of-life scenarios. The first scenario is the use of the blade material in a pedestrian bridge. The second scenario is the use of the blade material as fuel and raw material in a cement kiln, referred to as co-processing (Nagle et al., 2020). Both scenarios involve an amount of raw material that is substituted with the use of the blade material, and thus environmental gains are made through this material substitution. Three blades at 0.75 tonnes each were used in the reverse engineering and construction of the BladeBridge. Therefore, the functional unit for this assessment is:

2. The disposal of 3 * 0.75 tonnes of blade waste for 60 years

6.3.1 Environmental Assessment

6.3.1.1 BladeBridge and Conventional Bridge Comparison

The first data set compares the environmental impacts of functional unit 1. A single score comparison shows that the BladeBridge has a 14% reduction in overall environmental impact as compared to a conventional steel bridge (Figure 6.5).

The conventional bridge requires 18% more steel substructure and corresponding steel transport impact, twice the stainless steel parapet material, and 18% more epoxy coating during the maintenance cycles. The BladeBridge requires additional GFRP material for blade end caps and repair, concrete encasements at the bridge ends, and blade transport (Figure 6.6). However, the extra materials and transport required with the BladeBridge do not outweigh the impact due to the marginal differences in steel, transport, and maintenance required in the conventional bridge.

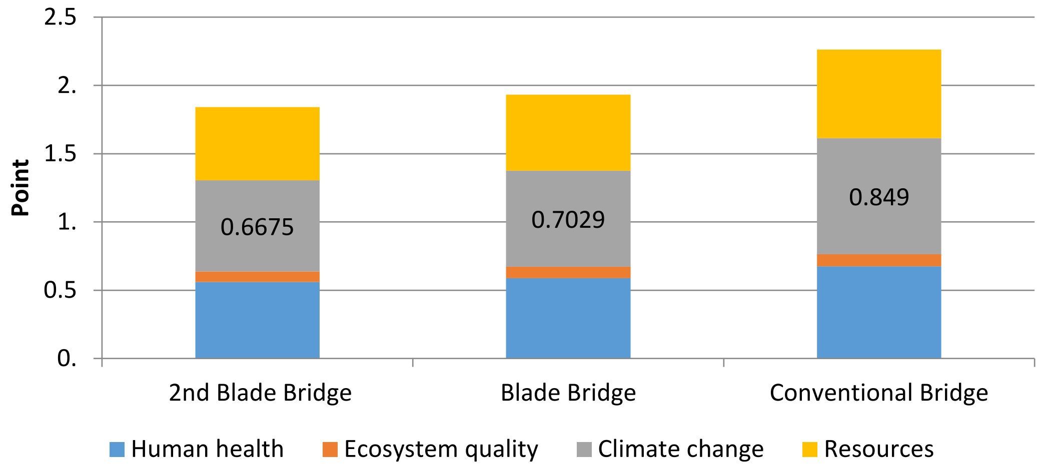


Figure 6.5 Single Score Comparison between blade-bridge and a conventional bridge

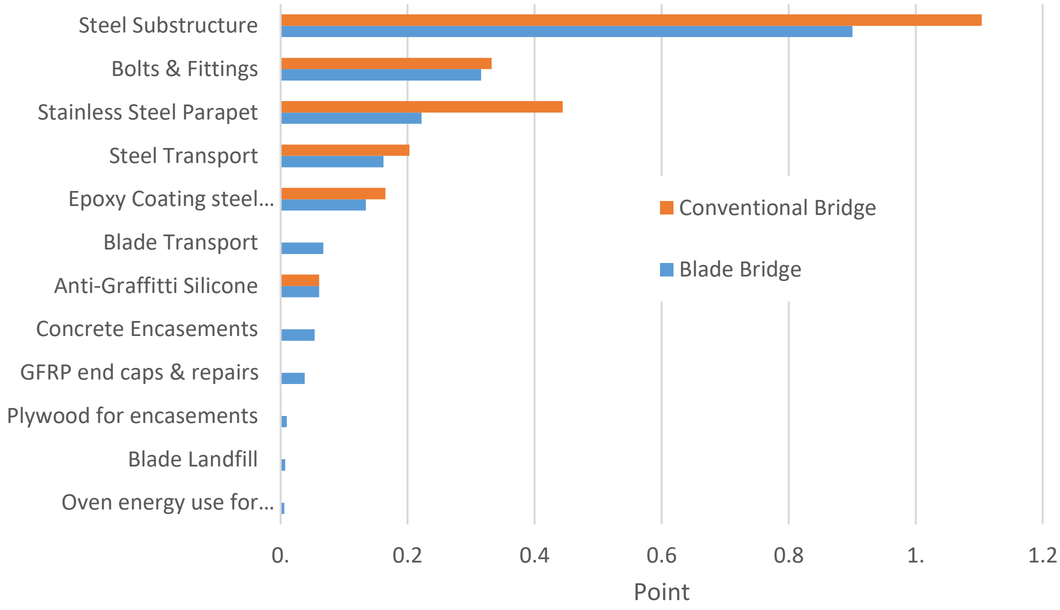


Figure 6.6 Single score impact comparison of the lifecycle inputs of both bridge designs

Not all impact categories are improved with the BladeBridge. Four of the 15 impact categories actually show dis-improvement with the BladeBridge. These categories are respiratory inorganics, aquatic eco-toxicity, land occupation, and aquatic eutrophication (Figure 6.7). All of these categories are negatively impacted by the use of the additional GFRP, concrete encasements, and formwork. Land occupation in particular, is 33% worse in the BladeBridge than in a conventional bridge, due to the requirement for plywood for the forms.

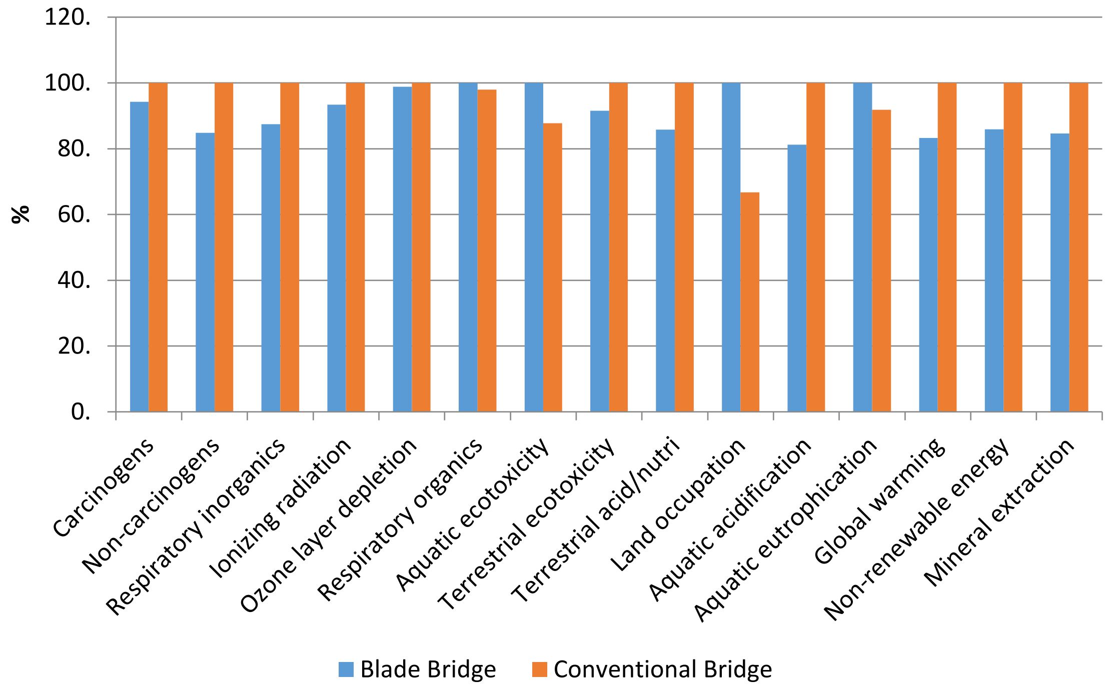


Figure 6.7 Impact Characterisation comparison between BladeBridge and a conventional bridge

For the second blade-bridge made from the same model, several impacts could be reduced. The oven energy for reverse engineering would be omitted. It is expected that 30% less bolts would be required for further bridges, thereby reducing the steel required by approximately 6%. Flipping the blades 180° to face the leading edge up rather than the trailing edge would mean that very little blade repair would be required, reducing FRP material by 10%. These modifications would result in a 1.5% reduction in overall environmental impact as compared to the first BladeBridge, using the single score assessment method. Climate change impacts are reduced by 17% with the first BladeBridge, and 21% with second and subsequent bridges (Figure 6.5).

6.3.1.2 BladeBridge and Co-Processing Material Substitution Comparison

The second data set compares the environmental impacts of functional unit 2. In the BladeBridge scenario, the material that was substituted was 561 kg of recycled steel (two side girders) and 289 kg of stainless steel (half of the stainless steel handrail). Co-processing data has been scaled from the study conducted in chapter four where the functional unit was 5.7 tonnes (Nagle et al., 2020).

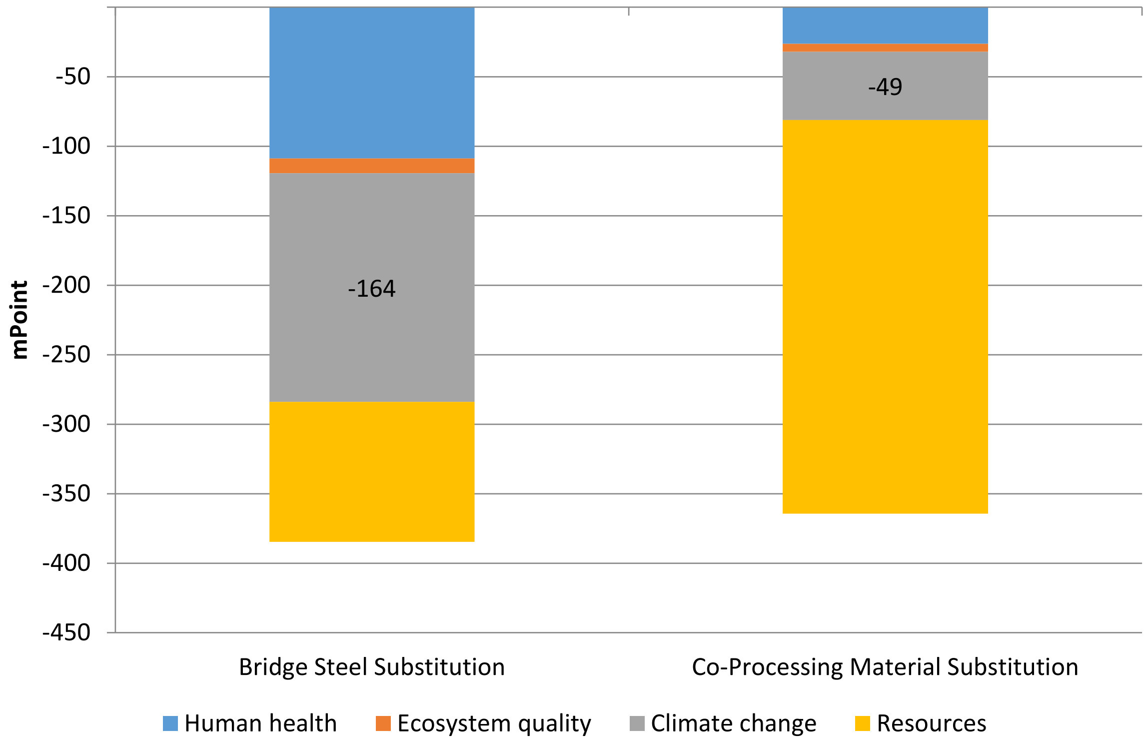


Figure 6.8 Single score comparison of the environmental impacts of utilizing 2250 kg of blade material in a BladeBridge and in co-processing

Use of the 2250 kg of blade material to substitute steel girders in the BladeBridge is 5% more beneficial than the use of the same material to substitute fuel, sand, CaO and aluminium oxide in cement manufacturing (Figure 6.8). Processing the material into cement will be the final use of this material, while use in a BladeBridge has the potential for the material to go onto third, fourth or additional lifetimes with consequential material substitution benefits at each phase. The final phase of the bridge material could ultimately be as cement, and while the impacts due to using blade material in cement processing will likely be less beneficial in 60 years or greater, there will still be some associated environmental gains.

From the perspective of CO_2 reduction, the use of the material in a BladeBridge offsets 0.164 Points of climate change impact, while Co-Processing offsets 0.049 Points of climate change impact. This is a benefit of 3.3 times the reduction in climate change impact through the use of the material in the BladeBridge. As defined in sections 4.2.3 and 5.3, data in this section has been normalized by dividing a damage category by the average impact of one European person per year (Humbert et al., 2014). Normalised categories are unit-less and are expressed in 'Points'.

6.3.2 Cost Comparison

6.3.2.1 BladeBridge and Conventional Bridge Comparison

The first cost assessment will compare the lifetime costs of the BladeBridge to a conventional bridge. The cost of the first BladeBridge was 7% higher than the conventional bridge, predominantly due to the labour required to reverse engineer the blade. 70% of the cost of the BladeBridge was labour, 29% was materials, and 1% was transportation of the blade. 21% of the labour cost was in reverse engineering the blade, included in A0 Pre-Construction work in Figure 6.9. However, a second bridge made using the same blade model can expect to be fabricated at approximately 30% less overall lifetime cost as compared to a standard bridge. The cost difference between the standard bridge and a second BladeBridge made from the same model blade would be due to a 30% reduction in steel material and galvanising as indicated in Figure 6.9 phase A1-A3, half the required parapet material as indicated in Figure 6.9 phase A5, and a reduction of 18% in the cost of maintenance at 20 and 40 years, due to the reduced surface area of steel that must be re-coated (B2 in Figure 6.9).

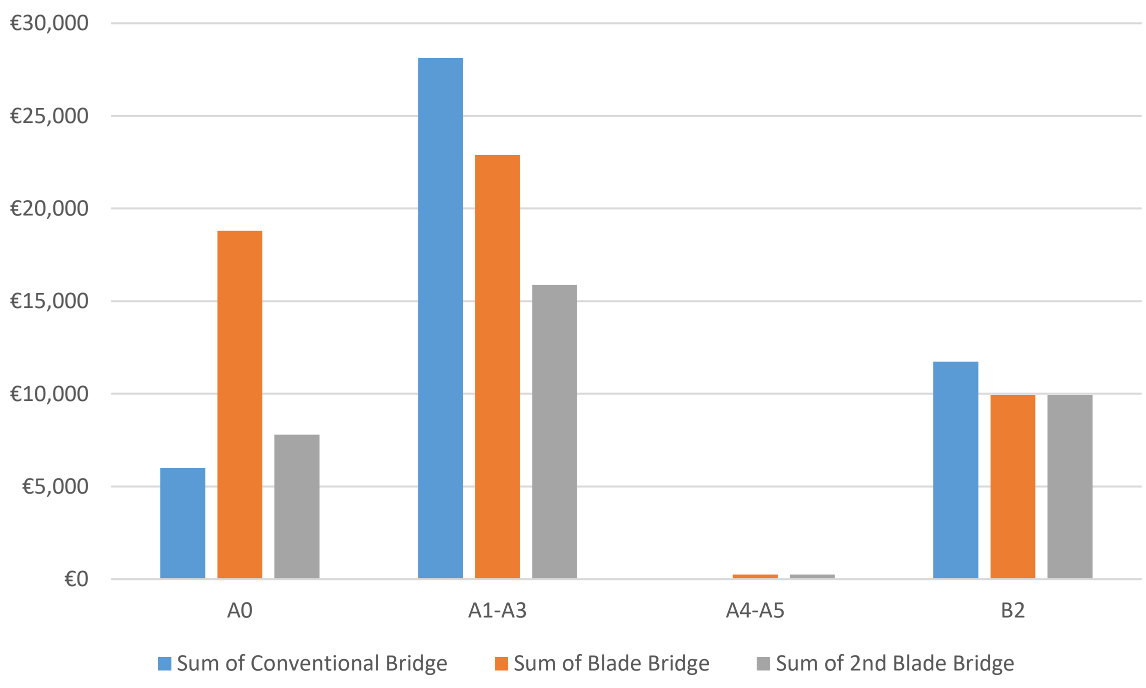


Figure 6.9 Cost comparison across the lifecycle phases for a conventional bridge, the BladeBridge, and a 2nd BladeBridge

The cost reductions achieved with a second BladeBridge made from the same model of blade include 26% savings by eliminating the reverse engineering which includes burnout test sample prep and testing, load test prep and testing, design team time, and the cost of transport of a third blade. An additional 7% cost reduction is achieved by reducing the fabricator design time, due to the learning curve of becoming familiar with the blade material and structure. Subsequent designs will contain more detail such that an inexperienced fabricator could more quickly replicate the bridge. A 2% saving could be made by flipping the blade over such that the trailing edge is facing down and not visible, and thus FRP touch-ups are not required. Third and subsequent BladeBridges from the same blade model with likely have further, although diminished, improvements.

Overall, the estimated cost for second and subsequent blade bridges is expected to be between €24,000 and €29,000.

6.3.2.2 BladeBridge and Co-Processing Costs

The second cost assessment will compare the cost to the wind farm owners to discard of 3 * 0.75 tonnes of blade material by either (1) Repurposing into BladeBridges, or (2) Disposal through co-processing. The disposal of unwanted blade material is in an early stage of market development, and the price point is evolving. Interviews with stakeholders offered insight into theoretical costs for co-processing of blade material, as well as the estimated market cost.

6.3.2.2.1 Cost to Wind Farms to dispose of blades by repurposing into BladeBridge

The cost to wind farm owners to dispose of 3 * 750 kg blades by repurposing into a BladeBridge simply involves the cost of transport. Up to five blades that are 14m in length or shorter can be transported by flatbed truck for the cost of a truck hire of approximately €700. A conservative estimate of €700 for the three blades, which are 13m in length, is made.

6.3.2.2.2 Theoretical Cost Estimate for Co-Processing

A theoretical cost estimate is calculated based on an interview with a wind farm owner who recently removed a 50m blade from site, as well as data on the gate fee at the blade processing centre Neocomp (WindEurope, 2020a). The costs are calculated at the point when the blade is lying on the ground, after being removed from the hub.

Cutting of the three blades into 3-5m sections will cost €1500. This includes labour of two people for the day, the cost of plastic protective film to collect the waste fibrous material, the rental of a 3-6 tonne lifting machine to aid in turning the blades, the rental of a cutting machine and multiple blade replacements, and health and safety considerations such as breathing apparatuses. A 14 m^3 skip hire costs €390, estimated transportation to a theoretical co-processing site in Ireland would be €700. The gate fee at Neocomp in Germany is €150/tonne, which amounts to a gate fee of €338 for the three blades for shredding, incorporation of the blade material into SRF, transport to the cement factory, and use as fuel and raw material substitution in the cement processing.

6.3.2.2.3 Market Cost for Co-Processing

Only one company in the Republic of Ireland is offering blade removal in which the end-of-life disposal is intended to be co-processing. This company offered an estimate of €10,000 per three 13m blades removed from the wind farm (after the hub had been removed and set on the ground) and an end-of-life certification issued for incineration or co-processing. Based on this quotation, the market estimate for co-processing of three blades as defined in the functional unit is €10,000 (Table 6.2).

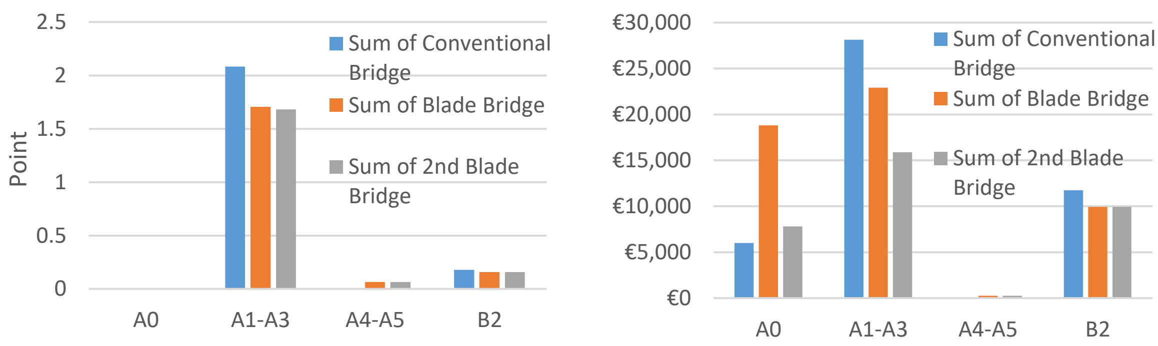
Table 6.2 Costs to wind farm owners to discard 2.25 tonnes of blade material

Process	Cost to the windfarm for BladeBridge option	Cost to the windfarm for co-processing (Theoretical)	Cost to the windfarm for co-processing (Market)
Blade cutting on site	N/A	€1500	N/A
Skip Hire	N/A	€390	N/A
Blade Transportation	€700	€400	N/A
Gate Fee for incorporation into SRF @ €150/tonne	N/A	€338	N/A
Market price for black box co-processing service	N/A	N/A	€10,000
Total	€700	€2,628	€10,000

Comparing the theoretical cost of co-processing to the cost of utilizing the blade material in BladeBridge shows €1,928 in value that could be shared between a BladeBridge business and the wind farm. A comparison between the quoted market price of co-processing of €10,000 and the cost to the wind farms to repurpose the material as a BladeBridge is €9,300. Sharing this value between the wind farm owner and a BladeBridge business would reduce the cost to construct a BladeBridge by €4,650.

6.3.3 LCA/LCC Combined Assessment

Considering the results of the LCA and LCC (Figure 6.10), the hotspot both in terms of environmental impact and cost is clearly at the manufacturing phase A1-A3, which matches the literature review. The BladeBridge's second highest cost impact is the pre-construction phase A0, which drops to nearly equal with a conventional bridge with the design and manufacturing of a second BladeBridge. The maintenance phase B2 is the third highest environmental impact and cost for all bridges, with the BladeBridges showing a decrease of 18% in maintenance costs due to the reduced surface area of steel requiring treatment. The construction phases A4-A5 include the formwork and concrete work around the cradles, and have the least environmental and cost impact.



(a) (b)

Figure 6.10 Assessment by lifecycle phase for all three bridge scenarios for (a) Environment and (b) Cost.

6.3.4 Circular Aspects for End-of-Life Options

End-of-life scenarios in 60 years' time could have been estimated using projected steel recycling rates, and estimations for future GFRP and concrete recycling or reuse. Recycling of steel will likely be 100% rather than the current industry average of 85% (World Steel

Association, 2012). GFRP recycling may be economically viable by this time, potentially offering substitution of glass material at a lesser quality, but little to no benefit from the epoxy portion. Transportation could be assumed to be fully electrified, and transported to a recycling site within 200 km.

However, quantification of the End-of-life (C1-C4) and Future Loads and Benefits (D) phases of the BladeBridge was omitted in lieu of a discussion of circular aspects of the bridge which might enable a wider range of end-of-life options for the material. This discussion follows a circular assessment framework developed in conjunction with the Dutch Infrastructure Agency (Coenen et al., 2021), and assesses the bridge project against the indicators and sub-indicators in the framework.

Design Input: The design input considers where the material came from, how much of it can be used again, and how robust the design is (Table 6.3).

Table 6.3 Design Input Assessment of BladeBridge

Sub-Indicator	BladeBridge Assessment
Recycled Material	All steel material was recycled at the rate of 85%. By mass, 75% of the material in the bridge is steel. Score: 0.64
Reused Material	By mass, 20% of the structural steel and parapet material in a conventional bridge was substituted by the use of the blades. Score: 0.2
Recyclable Material	By mass, 75% of the material in the bridge is steel, which will likely be 100% recyclable in 60 years. The blades make up 20% by weight. 70% of these can be recycled. The remaining 5% of the material is in the concrete encasings. These, as well as the encased blades, would be waste. Score: 0.89
Overdesign	By mass, overdesign is estimated at 6% by weight due to the excess bolts used. The blades are estimated to have a factor of safety of 4. Score: 0.7

Resource Availability: Resource availability considers a product's contribution to resource depletion. The BladeBridge scores very high in this category, as 25% of the material is waste FRP, which will be in overabundance and available locally in the coming years. Steel will continue to increase in recycling rates, so supply is estimated to remain steady. Score: 1

Adaptability: This indicator considers how easily the bridge can be adapted to changing needs (Table 6.4).

Table 6.4 Adaptability Assessment of BladeBridge

Sub-Indicator	BladeBridge Assessment
Broadening the Crossing	The BladeBridge cross beams could be easily exchanged for longer beams, or an additional blade and crossbeams added, allowing the bridge to be widened. Lengthening the crossing would be difficult due to the concrete encased cradles at the bridge ends. Score: 0.5
Broadening the Underpass	Bridge would be difficult to lift. Score: 0.3
Strengthening the Crossing	Layers of FRP could be added to the underside of the blades to strengthen the girders. Score: 0.8
Increasing Clearance	Difficult to break all the concrete encasing the bridge, so it would be difficult to lift. Score: 0.2

Reusability: Reusability considers the possibility for structural elements to be reused in another situation (Table 6.5).

The bridge scores well in its reliance on non-scarce material such as waste and fully recyclable steel. The use of standard cross and support beams, and steel decking is also favourable. However, the uniqueness of the blades and consequent bespoke fittings do not lend to adaptability and reusability. Design modifications could be made to the end supports of the bridge to not be encased in concrete, thereby improving the adaptability of the bridge design.

Table 6.5 Reusability Assessment of BladeBridge

Sub-Indicator	BladeBridge Assessment
Disassemblability	The steel components are all screwed or bolted together, and thus fully disassemblable. The blade would have to be cut inside of either encasement, reducing the material by 20%. Score: 0.8
Transportability	All pieces of the bridge are transportable by flatbed truck. Score: 1
Uniqueness	The cross beams are standard. However, the 20 deck connectors are bespoke and made to fit the unusual curves of the blade. The blade is also non-standard. Score: 0.3

6.4 Discussion

6.4.1 First comparative LCA and LCC of a BladeBridge

The BladeBridge project demonstrates that overall environmental gains of 14-18% can be made through the use of decommissioned blades to replace steel girders in a pedestrian bridge. The cost of the first bridge made from a specific blade model is more expensive due to €7,500 worth of reverse engineering required. Most of this testing could be avoided with access to the Original Equipment Manufacturer (OEM) blade design data, which has thus far been unavailable to the Re-Wind project due to IP concerns. However, cost reductions of up to 30% across the lifetime of the bridge could be achieved on second and subsequent bridges manufactured from the same blade model. The use of ISO 21931-2(2019) (ISO, 2019) enabled the comparison of environmental impact and cost at various phases of the lifecycle of the bridge, to identify hotspots.

A comparison of two end-of-life scenarios showed that using an amount of blade material to substitute coal and raw materials for clinker manufacturing is slightly less beneficial than substituting two steel girders in a pedestrian bridge. For the impact category climate change, the BladeBridge is 3.5 times more beneficial in reducing CO_2-equivalent emissions. However, this does not capture the full potential lifetime impacts of the material, as the blades in the bridge application could go on for third, fourth or more lives, and could then be used in cement manufacturing as a final end-of-life disposal. Quantifying the impacts of utilizing the material in clinker manufacturing at the end of the 60 year design life of the bridge would be guesswork, and thus, these calculations were not included. Finally, the cost to a wind farm owner to discard blade material through co-processing is estimated to be 3 times higher than to repurpose them as BladeBridges.

6.4.2 Design modifications to further improve LCA, LCC or Circularity

Design modifications that would improve upon the LCA/LCC would all include consuming more blade material, and substituting more steel material with blade material. Further cost reductions in labour could be gained by standardizing the deck to blade connections, to reduce engineer and fabricator design time. The size of blades that will be decommissioned will increase stepwise year on year. Currently, many of the available blades are 15m or less in length. The next increase in size will be to 22-25m in length. Blades of this size will have a proportionately wider max chord section, which results in the substitution of more handrail material. Larger blades will also be proportionately lighter in weight than their substituted steel parts. Installation of a conventional bridges with a span greater than 7m would likely require a heavier crane than would be required with an equivalent BladeBridge, thereby increasing the proportional gains made in the installation of a BladeBridge.

The next steps in substituting more of the bridge material with blade material might be to begin cutting standard size sections from the blades, and to set up a testing regime to determine how these sections could be used in a bridge substructure. The cost and environmental impacts due to the cutting and test regime would need to be assessed.

6.4.3 Recommendations for overcoming barriers in material repurposing

There are many barriers to repurposing construction material. As mentioned in the Introduction, they include quality concerns, unpredictable material availability, negative perceptions, and insurance and liability (Jensen and Skelton, 2018; Shooshtarian et al., 2020; Williams, 2020). Specifically for pedestrian bridges made from blades, barriers included economics, testing expertise, cutting of the blade to design, transport of the blade, and bridge foundation design (Jensen and Skelton, 2018). The following section describes how these barriers were overcome in this project, and what would need to be done to continue to overcome the barriers in order to scale up this research project into a business.

6.4.3.1 Barriers Overcome in the First BladeBridge

The initial contract was secured with the Cork County Council through a combination of underbidding other bridge contractors, a pre-existing working relationship between the bridge designer and the County Council, and a desire by the Council to commission something visibly different and sustainable on this particular greenway. The county council had many years of experience working with the bridge designer, and thus, trusted that this research project would be of high quality and would be seen to completion. The bridge was funded by the bridge designer's affiliated university, Munster Technological University, and thus, the county council got the bridge at a heavily discounted price. The blades were donated by Everun, also reducing the cost to the University.

Concerns around the quality of the material were overcome by extensive testing of a spare blade which had come from the same wind farm and had been stored in the same location. Visual inspection of the test blade showed it was in similar condition to the blades used in the bridge. Cutting of the blade and the testing methodology came from collaboration between a team member with 25 years of bridge design experience, and two other team members with 30+ years of FRP composites expertise. The bridge foundation design was also developed through this process. This collaborative testing and reverse engineering process was documented in a peer reviewed paper (Ruane et al., 2022). Insurance and liability were covered by the bridge designer's professional public indemnity insurance.

Concerns around negative public perceptions of using waste blade material in a bridge was assessed a year before the project commenced. The Re-Wind group held a community consultation with an anti-wind lobby group in Cork, to determine if any of the repurposing ideas for wind blades would be palatable to this group (Gough, 2022). The bridge idea was viewed as one of the most favourable.

6.4.3.2 Barriers for Scaling-Up BladeBridge

Predicting future material availability and costing the construction of a BladeBridge without university funding will be two additional barriers to scaling up the manufacturing of BladeBridges. Determining material availability would be done through working with wind farms well in advance of decommissioning, to determine blade quality and amounts. From this, the available material for BladeBridges can be determined. Overcoming barriers to scaling up is all part of determining a business model for the BladeBridge.

6.4.4 Business aspects of BladeBridge

A BladeBridge business model is two-sided, much like E-Bay, in that the business requires one customer to need to decommission blade material, and another customer to want to buy blade products. Scaling up a BladeBridge business will first require education of stakeholders on both sides of the business model.

Wind asset owners are an example of a customer segment on side one of the business models. They will need to understand the impending landfill ban, and the lack of availability of recycling options for blade material. The option of repurposing their blades will need to be included in their decommissioning contract, which will likely be drawn up 2-5 years ahead of time. Demonstrating the benefits of not only certifying that the blade material was not landfilled, but also quantifying the environmental gains achieved through repurposing their waste, could be important to asset owners.

Public procurement specialists in county councils are an example of a customer segment on side two of the business model. They will need to be educated on the option of procuring pedestrian bridges made with repurposed material. Many county council workers are unaware of Green Procurement requirements that are expected to come into effect in the next few years. The option for 'Alternate Tenders' must be selected when setting up tenders, to allow for bridges made from non-standard material to be considered. Contractors bidding for greenways are a second example of a customer segment on side two of the business model. They must be educated on the existence of BladeBridges, and the ability for a more circular bridge to make their tender stand out. To offer this education, the Re-Wind research group must first complete the technical approval process (Transport Infrastructure Ireland, 2019b) to prove reliability of the BladeBridge.

Figure 6.11 is a graphical description of the costs to both customer segments, and how they are expected to change over time. The cost of blade disposal is currently high, due to a lack of other alternatives at present. It may spike slightly around the time of the landfill ban in 2025 (A). However, developments in recycling GFRP material may be spurred on by this ban, increasing end-of-life options for blade material which may bring down the cost to a wind farm owner of blade disposal (B). At the point in which recycling of GFRP becomes profitable, wind farms can begin to sell on their blades rather than being charged to take them, as represented by a negative number (D). The earlier timeframe in which blade disposal is high

(~2022-2025) is the time in which to develop BladeBridge, by undercutting the cost to the windfarm of disposal, and putting this value towards reducing the price of a BladeBridge. BladeBridge can be successful in the market by undercutting the cost of a conventional bridge, until the point in time when GPP requirements may come in (C). After this time, a more robust procurement process in which the value for reduced environmental impacts and the issuance of an EPD or waste diversion declaration is included in the tendering requirements, may allow for charging more for a BladeBridge than a conventional bridge (E).

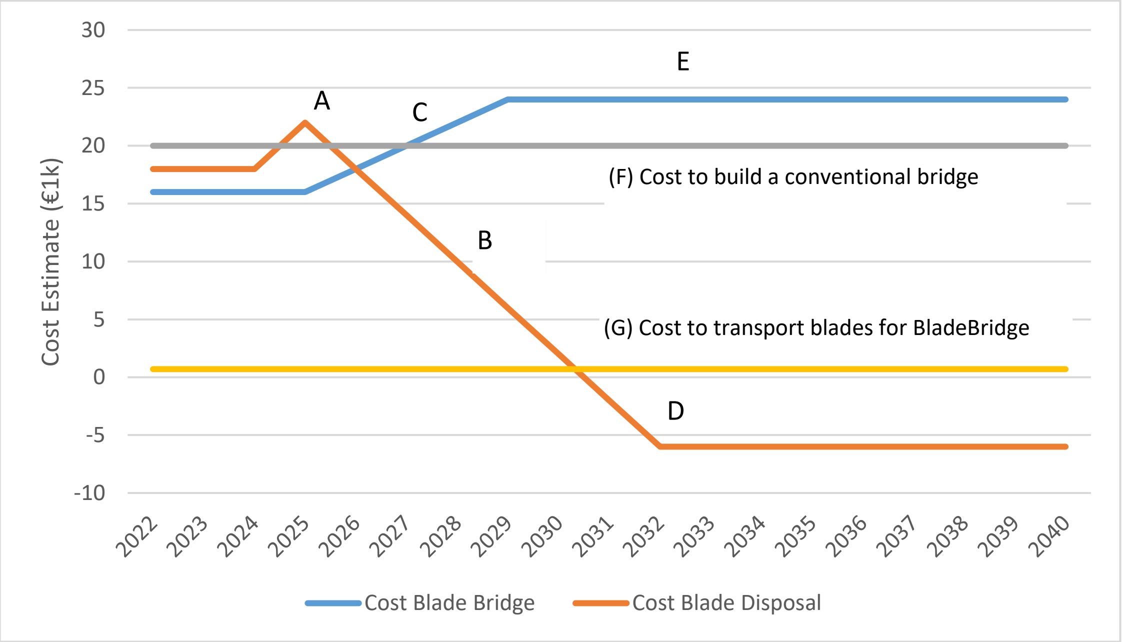


Figure 6.11 Cost versus time estimates for BladeBridge business, considering the impending landfill ban in 2025 and the introduction of GPP requirements

Another consideration of scaling up a BladeBridge business is whether to attempt to manage the blade material within or outside of the waste regime. Blade material will enter the waste regime if the asset owners specify it as waste in their decommissioning contract. To handle this material requires a waste permit, and to repurpose the material requires certification of end of waste of the material, both of which require additional time and costs. However, entering the waste regime has the benefit of contributing to the national statistics on the quantification of waste repurposing, potentially increasing Ireland circular material use number.

6.5 Conclusions

Decoupling renewable energy generation from waste production is a challenge that not only Ireland, but the entire world, is facing. The BladeBridge project has the potential to help with this challenge by repurposing waste material from the renewable energy sector. To scale this project into a business that can actually repurpose large volumes of blade material, various aspects of a BladeBridge business must be assessed. From the perspective of a wind farm customer, using decommissioned wind blades in the construction of a BladeBridge is less impactful environmentally, and significantly cheaper. From the perspective of a bridge procurer, the BladeBridge is less impactful environmentally and cheaper for the second and subsequent bridges made from the same blade model. If the marginal cost between co-processing and acquisition of the blades in order to make a BladeBridge is paid by the wind farm owners, the cost to build a BladeBridge could be less than a conventional bridge. This study is a first indication that a BladeBridge business could be created from this project. As the final compliment to this environmental and cost assessment, an assessment of the potential social impacts must be completed.

The following chapter develops social indicators for the assessment of a BladeBridge product idea, which are used in the final thesis chapter to complement the LCA and LCC for a full LCSA of the BladeBridge.

7 Sustainable Development Goals and Life Cycle Thinking as a Foundation to Developing Purpose Driven Businesses

7.1 Introduction

The research presented thus far has focused on environmental assessment of multiple end-of-life options of blade material in Ireland. Chapter four assessed the current disposal methods for Irish blade waste. Chapter five performed a comparative sustainability assessment of repurposing of wind blades into both publicly and privately commissioned structures, with a focus on the potential for supporting job creation, and raising awareness of sustainable supply chains. Job creation and supply chains typically exist in the context of business, and therefore a business would need to be formed in order to impact on these. Chapter six was an environmental and economic case study of the BladeBridge project, and finished with an initial assessment that the project should be further assessed for its potential to become a business.

The demand for 'purpose driven business' is re-gaining popularity, with Marc Benioff of Salesforce stating, "The business of business is improving the state of the world (Williams-Grut, 2020)." However, for businesses to do this, they must design their products and develop their business models under a set of criteria that will truly result in measurable improvements.

7.1.1 Background

In September 2015, a set of 17 Sustainable Development Goals (SDGs) were adopted by all 193 member-states of the United Nations (Figure 7.1). These goals outline how the world could become more sustainable, prosperous and peaceful through economic, environmental and social sustainability practices (UN General Assembly, 2015). Negotiating the Goals was a landmark achievement and represented the most comprehensive set of global indicators that the world has ever seen. Intergovernmental facilitation of this difficult task was co-performed by the Kenyan Ambassador to the UN, and Irish Ambassador to the UN, David Donoghue.

Seven years on from this momentous event, and the Irish performance against the SDGs has been disappointing, with Ireland ranked 11th out of 15 in 2021 (Clark and Kavanagh, 2021), 10th out of 14 in 2022 (Clark et al., 2022), and having been noted as having a 'profound waste management problem' (Coalition 2030, 2018).

Figure 7.1 The United Nations Sustainable Development Goals (United Nations, 2015)

This chapter will argue that in order to begin to correct this shortfall, Irish businesses should become more proactive in engaging with the SDGs. The SDGs should be the set of criteria that all development is first benchmarked against. A Life Cycle Sustainability Assessment (LCSA), informed by the SDGs, can offer a set of criteria to guide early product design and business model development of a 'purpose driven business.' Businesses who strive to be purpose driven will become reliant on these measurable indicators in attracting customers. Businesses will quickly realise that alignment with the SDGs will open up business opportunity, while the potential risk of not doing so will become more detrimental. This SDG based set of criteria will then be applied in the following chapter, to determine if the case study of the BladeBridge is a product worth making.

7.2 The Sustainable Development Goals and Life Cycle Sustainability Assessment

In this chapter, the SDGs and the concept of life cycle thinking are brought together. Life cycle thinking means being mindful of the sustainability throughout the entire lifetime of a product from raw material extraction to disposal at the end-of-life. , The concept of life cycle thinking can be applied to purchases, transportation, food consumption and even services. Sustainable developments means "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). One way of measuring sustainability is through a LCSA. A LCSA includes environmental Life Cycle Assessment

(LCA), Life Cycle Costing (LCC) and social Life Cycle Assessment (s-LCA), as discussed in previous chapters. LCSA and the SDGs, it seems, should go hand in hand. However, because the SDGs were initially top-down policy guidance and each can include multiple aspects of sustainability while LCSA is more often used from a product perspective, aligning the metrics is not straightforward. The next section will describe how they can be used together, to support businesses as they work towards the SDGs.

7.2.1 Business Opportunity and Responsibility

Many companies view the SDGs as government's responsibility (PwC, 2015). However, referring back to the Embedded Systems Model in chapter two, businesses cannot succeed in societies that fail (Vanasupa et al., 2010), and there is increasing concern that climate change, corruption, and mass migration could result in a failing society. With this in mind, the SDGs should be considered the planet's Key Performance Indicators (KPIs). Businesses should make it their responsibility to immediately incorporate them, and to encourage their supply chain to follow suit. In support of this, a study by The Business and Sustainable Development Commission has shown massive opportunities for businesses who adopt the SDGs fully into their planning and practices. The opportunities would be realised through the following positive actions and outcomes: (1) Regaining brand trust, (2) Quantification of the integration of externalities, and (3) Working with governments to design sector-wide legislation (Business & Sustainable Development Comission, 2017). These actions, supported by and in support of the SDGs, would also require LCSA inputs. The following sections explore these three topics and show where both the SDGs and LCSA play a part.

7.2.1.1 Regaining Trust

A growing awareness of the effects of cheap food and fashion on developing countries and disadvantaged areas at home has made customers question their products and become confused. With few ethical rating systems in place to give customers confidence in the effects of their purchases, customers rely on sources such as social media, news reports information from friends and documentaries, and in making their decisions. Regaining brand trust could be a huge market opportunity for businesses. Sentiment is growing that business has to take responsibility for the full lifecycle impacts of their products, and that people are looking to them to do this. The Edelman Trust Barometer 2022, a survey of 36,000+ people in 28 countries, shows that worldwide trust in business is higher than in NGO's, the Media, and even in Governments (Edelman, 2022), and that people are looking for business to do more to address societal issues such as climate change, economic inequality and systemic injustice. Figure 7.2 shows that far more people want businesses to do more to address aspects of sustainability versus people who feel businesses are overstepping their responsibility. Finally, of the top ten international trust issues, the final three were business related expectations: Business need to step up on societal issues, societal leadership is now a core function of business, and business must lead in breaking the cycle of distrust (Edelman, 2022).

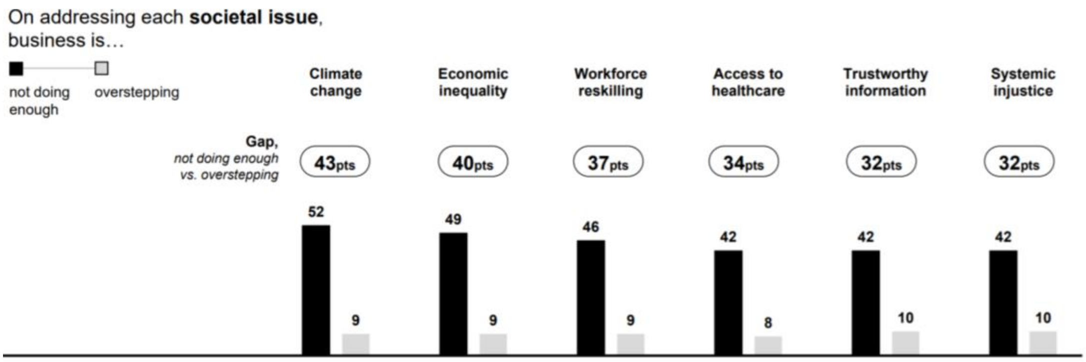


Figure 7.2 Expectations for businesses to address societal issues (Edelman, 2022)

Elements of LCSA can be used to help businesses respond to this. Environmental Product Declarations (EPDs) and Product Environmental Footprints (PEFs) are generated from professionally verified product LCAs. Fair Trade is a third party verified certification that is based on s-LCA assessments. These publicly accessible, trusted certifications can verify a company's efforts in support of selected SDGs. This public accountability can greatly improve brand trust.

7.2.1.2 Pricing and Integrating Externalities

'Externalities refers to situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided.' (stats.oecd.org)

Externalities are built into many current business models. Intensive pig farming might result in air pollution that impacts on the health of local residents, causing them to pay for doctor's visits or lose out on salary due to unpaid sick leave. Chemicals dumped by a manufacturing plant into a body of water might kill fish, thereby affecting the livelihood of fishermen. When a business causes damage and does not pay for it, this is an externality. At the same time, it can be very difficult to determine which products have externalized costs. As customers become more aware of the detrimental effects of social and ecological side effects, businesses need to be prepared to prove that they are not creating externalities. This is where LCSA can play a role in supporting the SDGs, by quantifying the social and ecological impacts of a product or process. With well supported geographical and temporal boundaries, these impacts can be quantified, and the costs to mitigate these impacts included as business expenses. Including, rather than externalising these costs will begin to level the playing field between products and businesses which currently have different degrees of sustainability (Business & Sustainable Development Comission, 2017).

7.2.1.3 Business Involvement in Legislating for a Level Playing Field

Businesses that have incorporated sustainability into their practices already have done so at somewhat of a risk. Not all customers will see more value in a product made with sustainable business practices than they will in a product that costs less. Using LCSA to quantify and include externalities in pricing is the start to levelling the competition between sustainable and unsustainable products. Businesses need to know that if they have no externalities, are paying living wages to their employees and ensuring the same across their supply chain, that they will not be at a financial disadvantage. This is where government legislation comes in.

The SDGs are a voluntary set of agreements, in which 193 countries have agreed to abide by. Businesses would be smart to anticipate stricter rules coming in, and to ready their businesses for this rather than scrambling to react after the rules come in. An even better approach would be for businesses within a sector to band together to form recommendations for sector wide rules complying with the SDGs. An example of this was in June 2021 when the European wind energy sector called for an EU wide ban on landfilling of blade material by 2025 (Wind Europe, 2021b). This anticipated ban will put pressure on the industry and associated supply chains to develop more circular end-of-life alternatives for the blade material, thus increasing the sector's overall sustainability. Calling for this ban at a set time in the future means each company within the sector has time to build its compliance strategy, while still staying in business. A knock-on effect from the impending ban may be the creation of a market demand for waste diversion quantification for the end-of-life disposition of blade material. This 'waste diversion declaration' would be issued to wind farm owners who chose to have their blade 'waste' repurposed. After the blades had been repurposed, it would quantify the amount of diverted environmental impact achieved through the repurposing of their blade material, thereby allowing the generators of 'waste' material to share in the benefits of repurposing this material.

The declaration, which would include an LCSA with third party verification, could further drive innovation and value creation in the development of repurposing of unwanted material.

7.2.2 ‘Think Globally, Act Locally’

On 19th August, 2019, the Business Roundtable released a new statement on the ‘Purpose of the Corporation’, that the 181 CEOs who signed the statement were committing to lead their companies for the benefit of all stakeholders, not just the shareholders (Business Roundtable, 2019). Stakeholders included employees, customers, communities, suppliers and the world. At the World Economic Forum in Davos, January 2020, Marc Benioff, Chairman of Salesforce, stated that ‘every CEO has a responsibility to think about all stakeholders. And yes…the planet is a key stakeholder.’ (Williams-Grut, 2020). This approach to capitalism, termed ‘Stakeholder Capitalism’, moves back to an older tradition in which business is an integral part of a society, rather than just a purely economic institution (Freeman and Liedtka, 1997). Businesses who want to consider their stakeholders will need tools to do this. While LCA and LCC are regarded as well-established frameworks with ISO standards, s-LCA is still being developed. s-LCA is about identifying impacts on people, both positive and negative, and therefore the s-LCA framework calls upon a stakeholder approach (Benoît Norris et al., 2020). s-LCA can support the move towards ‘stakeholder capitalism’ by assessing an organisation’s direct or indirect impact on its stakeholders. S-LCA indicators are grouped based on stakeholder categories, such as Workers, Local Community, and Value Chain Actors, in order to identify hotspots. Some s-LCA indicators under these categories include Fair Salary (Workers), Community Engagement (Local Community), and Promoting Social Responsibility (Value Chain), among many others.

A regional approach to choosing s-LCA indicators can be used, although it must be noted that the s-LCA guidelines discourage this in order for studies to be used comparatively (Benoît Norris et al., 2020). However, in this study, we will explore the use of starting with regional needs to inform indicator selection. Regional indicators assist an organisation in assessing their product or business structure’s ability to respond to regional or national issues (Balkau et al., 2021). In Europe, regions are classified using the Nomenclature of Territorial Units for Statistics (NUTS) classification , for the purposes of generating regional statistics for comparison of similarly populated areas (European Commission, 2011). The NUTS 1 population threshold is 3 million to 7 million people, and therefore the entire country of Ireland, with a population of just over 5 million, falls under this NUTS category. Therefore, the region that this study focuses on is the Republic of Ireland, while the 'regional or national issues' were identified as the SDGs in which Ireland is demonstrating the greatest shortfall. Patrick Geddes, a Scottish sociologist and pioneering town planner from the early 1900's, promoted an interdisciplinary approach to understanding 'regional' needs when planning a city. His mantra was to 'think globally, act locally' (Geddes, 1915). In this vein, this chapter presents a framework for thinking globally by starting with the SDGs for project planning, but acting locally by considering regional needs, as measured by national SDG shortfalls.

To identify 'regional need', Social Justice Ireland's (SJI) 2021 annual Sustainable Progress Index was consulted. The report ranked Ireland 11th out of 15 EU countries for progress against the SDGs (Clark and Kavanagh, 2021), falling 10th for Economy, 6th for Society, and 15th for Environment. The report noted that Ireland has some 'persistent' sustainability issues, and should focus on rebalancing economic and social progress with impacts on the environment (Clark and Kavanagh, 2021). Social Justice Ireland grouped the SDGs into the following sustainability categories (Clark and Kavanagh, 2021):

- Economy: SDGs 8, 9
- Society: SDGs 1, 2, 3, 4, 5, 10, 16, 17
- Environment: SDGs 6, 7, 11, 12, 13, 14, 15

The United Nations Environmental Program Guidelines for Social Life Cycle Assessment states that s-LCA has strong ties to ten of the SDGs (Benoît Norris et al., 2020). These include all of those listed under 'Society' in the SJI document, plus two additions: 8 - Decent Work and 12 - Responsible Consumption.

Figure 7.3 Ireland's performance against the SDGs in 2021 (Sachs et al., 2021)

Figure 7.3 from The Sustainable Development Report in 2022 is a dashboard of Irish performance against individual SDGs (Sachs et al., 2021). Ireland demonstrated 'Major Challenges' for SDG 2 - No Poverty, SDG 12 - Sustainable Consumption and Production, SDG 13 - Climate Change, and SDG 17 - Partnership for the Goals, as indicated in red. 'Significant challenges' were identified for SDGs 5 - Gender Equality, SDG 7 - Affordable and Clean Energy, SDG 9 - Industry, Innovation and Infrastructure, and SDG 14 - Life under Water, as indicated in orange.

To assess a product or process for its ability to positively impact regional needs, an LCSA could be performed using s-LCA indicators based on regional performance gaps in the SDGs categorized as 'Social'. In Ireland, the 'social' SDGs listed in red and orange would be the indicators to start with. For Ireland, this would be SDGs 2, 5, 12, and 17. The 47 Sub-indicators for these goals are listed in Appendix Table A.5.

7.3 Case Study – The Blade Bridge

The proposed framework for establishing s-LCA indicators based on regional needs as identified by national shortfalls in the SDGs will now be tested on a case study. The Greenway Bridge, as described in the previous chapter, is used as the case study.

First, a list of stakeholders is compiled based on the two customer segments which correspond to two functional units, as established in chapter six. To recap, the blade bridge should be assessed based on two functions:

1. The blade material as raw material for the construction of a pedestrian bridge
2. The blade material as a waste product that needs to be dispositioned

Based on these two functions, stakeholders were identified as: Wind farm owners who initially disposed of the blades; the blade 'waste' handlers or decommissioning companies; the Department of Energy and Climate Change (DECC) or landfill owners who would have had to deal with the waste; cement manufacturers; the general contractor who transports the blades and the final blade bridge product; the blade bridge designer; the fabricator; local businesses who benefit from being close to what could become a tourist site; the county council who commissioned the work; walkers and cyclists who use the bridge; Wind Energy Ireland who are interested in more sustainable end-of-life solutions for the blades from a sector-wide image perspective; and finally, children who see the bridge and become inspired to become Future Designers of more circular products themselves (Table 7.1).

Table 7.1 Stakeholders for s-LCA, categorized according to the s-LCA guidelines

Worker	Local Community	Value Chain	Consumer	Society	Children
Fabricator	Local Businesses	De-commissioner	Cyclists	DECC	Future Designers
Contractor	Local Groups	Wind Farm Owners	Walkers		
Designer		County Councils			
		Wind Energy Ireland			
Researcher		Cement Manufacturers			

The list of 47 sub-indicators in Appendix Table A.5 was narrowed down to five, based on a whether each indicator was applicable to the identified stakeholders. Below is a description of this.

12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse

Stakeholders: De-commissioner, Wind Farm Owners, DECC, Wind Energy Ireland, local groups, cement manufacturers.

Explanation: Waste reduction will improve the image of wind farm owners and the wind energy sector (represented as the industry group Wind Energy Ireland). The DECC will have less waste to manage, and the planet will have less raw materials extracted (which is simply mentioned here, as it will be measured separately through LCA). It is possible that this will negatively impact on the business operations of de-commissioners, who often also operate as waste handlers. However, in the researcher's experience, the waste handling company will pay more to send the blade to landfill than to transport the blades to a remanufacturing site. Therefore, this project would likely enhance the operations of the de-commissioning companies. Local groups may be impacted depending on their area of focus. For example, anti-wind groups may not like to see the blades repurposed, while groups such as Tidy Towns may see the benefit in repurposing discarded construction material.

12.7 Promote public procurement practices that are sustainable, in accordance with national policies and priorities

Stakeholders: Cork County Council, DECC

Explanation: The Irish county councils will be required to select projects that are measurably more sustainable, in support of green public procurement, and as directed by the DECC.

12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature

Stakeholders: Fabricator, designer, contractor, researcher, wind farm owners, cyclists/walkers, future designers (children).

Explanation: Public demonstration of the circular economy to members of the public such as walkers, cyclists and children will increase awareness of sustainable development. Giving fabricators, designers and contractors the opportunity to work on a project that reuses waste increases innovation and skill capacity.

17.14 Enhance policy coherence for sustainable development

Stakeholders: County Councils, Wind Energy Ireland, DECC, cement manufacturers

Explanation: Raw material substitution by repurposing end-of-life wind blade material will help to make renewable energy cleaner while simultaneously supporting circular economy efforts. This supports both SDG 7 (Affordable and Clean Energy) and SDG 12 (Sustainable Consumption and Production), by allowing the achievement of national renewable energy goals while improving the circularity of construction waste. This contributes to policy coherence for sustainable development, and directly addresses the observation that Ireland should rebalance economic and social progress with environmental impacts.

17.17 Encourage and promote effective public, public-private and civil society partnerships, building on the experience and resourcing strategies of partnerships

Stakeholders: (All) Fabricator, Contractor, Designer, Researcher, Local Businesses, Local groups, De-commissioner, Wind Farm Owners, County Councils, Cyclists/Walkers, DECC, Wind Energy Ireland, Future Designers, cement manufacturers

Explanation: This sub-indicator captures potentially the most important benefits of the blade bridge project. When researchers design a bridge using decommissioned wind blades and the county councils, spurred on by green procurement requirements, choose to commission the bridge, this allows for upskilling and capacity building along the supply chain. To build the bridge, fabricators and contractors must learn to work with this waste material, which spurs innovation in the use of new materials. When researchers source blade material from de-commissioning companies, these companies begin to see a value in material that was previously landfilled. The wind sector (wind farm owners and Wind Energy Ireland), will be prohibited by the DECC from landfilling blades, which may spur on financial support for more bridges. Validation of the end-of-life disposition of the blades may create a new business of waste diversion declarations, in which wind farm owners receive reports quantifying the end-of-life impact of their blade material. Finally, cyclists and future designers will see the bridge, and bring this awareness of circularity back to their everyday lives.

7.4 Conclusions

Chapter five called for a sustainability assessment of repurposing ideas for wind blade material, with a focus on the potential for these ideas to impact on job creation and awareness raising of sustainable supply chains. Job creation and supply chains typically exist in the context of business, and therefore, indicators that assist in building sustainable, or purpose driven businesses must be utilized. Chapter six called for further business viability assessment of the BladeBridge project. This chapter has proposed that the SDGs should be incorporated into early business planning and product development through the use of Life Cycle Sustainability Assessment.

Following the idea of ‘Think Global, Act Local’, this chapter suggests using identified national shortfalls in the SDGs to form s-LCA indicators, for use in LCSA at early stage product and business development. By considering these areas of improvement in the social assessment of a LCSA, a project is better positioned to grow into a purpose driven business by addressing local need. SDGs that were categorized as ‘social’ were 1, 2, 3, 4, 5, 8, 10, 12, 16, and 17.

SDGs identified as needing significant improvement in Ireland were 2, 5, 7, 9, 12, 13, 14, 17. Therefore, the overlap resulted in 2, 5, 12 and 17, which in total had 47 sub-indicators.

This indicator selection process will be tested on the case study of the blade bridge, which was discussed in the previous chapter. 13 stakeholders were identified for the blade bridge case study based on two functions that the blade material could serve. The 47 sub-indicators were then filtered based on their relevance to these stakeholders. This resulted in five applicable sub-indicators, which will serve as s-LCA indicators for a blade bridge constructed in Ireland. This selection process could be applied to other product and business development exercises in many other sectors and regions. These five s-LCA criteria will now be used in the following chapter in a full LCSA of the blade bridge.

8 Sustainability Analysis of a BladeBridge for Early Business Planning

8.1 Introduction

The BladeBridge LCA and LCC were detailed in chapter six. This chapter will apply the s-LCA indicators developed in chapter seven to build on the LCA/LCC in order to conduct a full LCSA of the BladeBridge.

8.1.1 Life Cycle Sustainability Assessment

LCSA includes LCA, LCC and s-LCA (Valdivia et al., 2013), and aims to provide a broader, more holistic perspective to sustainability assessments. The s-LCA framework, as defined by the UNEP Guidelines, has strong links with the SDGs (Benoît Norris et al., 2020), whose application to business and product development, and to Ireland, were discussed in chapter seven. The SDGs are becoming the focus of public policy discussion, as citizens become progressively more interested in social well-being and the environment, rather than just economic growth (Clark and Kavanagh, 2021). LCSA and the SDGs are increasingly being combined in research (Maier et al., 2016; Wulf et al., 2018; Zeug et al., 2021). They were used in a previous study to provide a 'comprehensive, objective and fair way' of assessing the sustainability of five end-of-life solutions for wind turbine blades in Ireland, (Deeney et al., 2021), as well as in indicator selection for an LCSA of hydrogen production (Wulf et al., 2018). As discussed in the previous chapter, more businesses and organisations are defining their purpose against the SDGs, and more projects are aligning their indicators against the goals. Including s-LCA indicators informed by the SDGs in an LCSA of the blade bridge can contribute to the planning stages of a 'purpose driven' and sustainable product or business.

LCSA methodologies vary considerably, with some studies fully incorporating the three pillars of s-LCA, LCA, and LCC into multi-criteria decision making (MCDM) tools, and others studying the three separately (Kühnen and Hahn, 2017). Many studies are highly operationalized and additive, based on the three pillar approach to sustainability (Figure 8.1). This requires the three dimensions to be 'standardised, harmonised, and synchronised' and then added together, which is less transparent than the integrated approach and potentially misses many of the qualitative interactions between the three dimensions (Zeug et al., 2020).

Figure 8.1 Three pillar approach of sustainability (World Steel Association, 2020)

An additive approach also does not take into account the reality discussed in the Literature Review, that the economy is embedded in society, which is embedded in the environment (Vanasupa et al., 2010), and that the economy cannot exist outside of society or the environment (Figure 8.2).

Figure 8.2 The Embedded Systems Model of sustainability, recreated from (Vanasupa et al., 2010).

The research in this chapter combines the LCSA framework with the embedded systems model of sustainability to form a stage-gate framework for early product sustainability assessment. This framework, which performs an individual rather than additive LCA, LCC, and s-LCA, can contribute to an iterative assessment of a product's ability to contribute to a purpose driven business.

8.2 Methodology

The foundation of this framework is the embedded systems model of sustainability (Daly, 1990; Vanasupa et al., 2010). This model implies that if the earth is not healthy, we will not have a healthy society within which to have an economy. The earth supports society, which in turn supports the economy. With this in mind, we can propose that the first screening of any new product, service, or business idea should be an environmental assessment. The second should be an assessment of the potential benefits or damages to society. Only after consideration of the impacts to the environment and society, which determine if a product offers improvements, should business or economic viability be assessed. The ordered combination of these three assessments determines if a product is actually worth making (Figure 8.3).

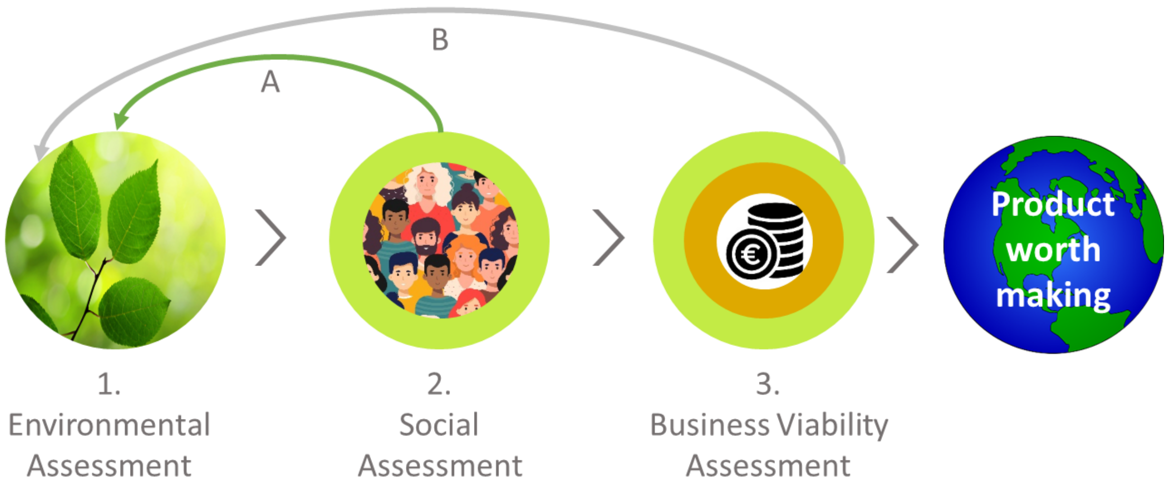


Figure 8.3 LCSA framework based on the embedded systems model, including a stage-gate assessment criteria

A Stage-Gate approach is a project management technique in which a project is divided up into stages, with decision points, or gates, allowing progress to the next stage (Phillips and Broughton, 1999). In this framework, the stage-gate approach is adapted to the embedded systems model, to encourage impact assessments to be completed in order of importance. This innovative approach will flag and force early design modifications if a product is found to be damaging or less beneficial, first environmentally and then socially.

The LCSA will follow the LCA/LCC methodology outlined in chapter six, with the addition of an s-LCA, as described below.

8.2.1 Social Life Cycle Assessment Overview

To round out the LCA/LCC into a sustainability assessment, an s-LCA assessment methodology is proposed. Per the UNEP s-LCA Guidelines (Benoît Norris et al., 2020), Step (1) Goal and Scope definition match the LCA/LCC, but with the addition of a list of stakeholder categorization and involvement. BladeBridge project stakeholders were identified and categorized in chapter seven, and a set of s-LCA indicators was developed using the stakeholder list to filter SDG sub-indicators. To recap briefly on the choice of using the SDGs to inform the s-LCA indicators: the SDGs can be considered the world's key performance indicators, and thus bring in the global aspect to 'thinking globally, while acting locally' (Geddes, 1915).

The BladeBridge product is then assessed against this set of s-LCA indicators using a generic ascending reference scale for social performance evaluation, from section 5.2.1.1 in the s-LCA Guidelines (Benoît Norris et al., 2020) (Figure 8.4). The results of the s-LCA assessment are then incorporated into the LCSA as described in the Stage-Gate Criteria section below.

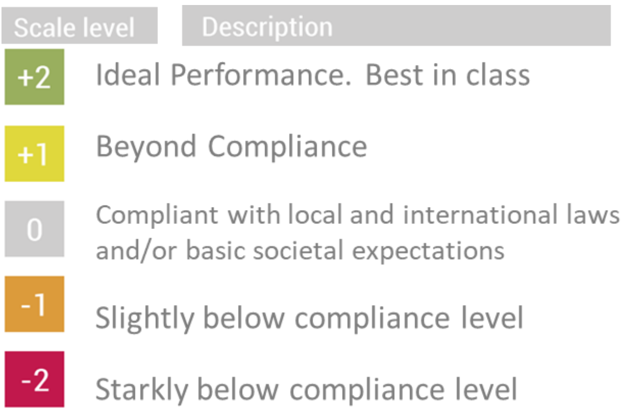


Figure 8.4 Generic ascending reference scale for social performance evaluation (Benoît Norris et al., 2020)

8.2.2 Goal and Scope Definition

The goal and scope of this study are similar to the case study in chapter six. The goal is to compare the potential sustainability of the life cycle of a pedestrian bridge made using decommissioned wind turbine blades against existing baseline products. From a business development perspective, this project has two potential end customers, and will therefore have two corresponding functional units. The functional units and temporal boundary match those of the LCA/LCC study in chapter six, which is described below:

- Customer Segment A: Public procurers of cycleway bridges
  Functional Unit A: 22m^2 pedestrian bridge with emergency vehicle load capacity of 12 tonnes, over 60 years
- Customer Segment B: Wind farm owners with unwanted GFRP blade material
  Functional Unit B: The disposal of 3 * 0.75 tonnes of blade waste for 60 years

The baseline product for customer segment A will be a conventional steel bridge, detailed in chapter seven. The baseline product for customer segment B will be co-processing of the material into cement, detailed in chapters four and seven.

The temporal boundary of 60 years was chosen based on the engineering design of the BladeBridge, combined with guidance on the design working life of a GFRP bridge in the UK (CIRIA C779, 2018).

8.2.3 Stage-Gate Criteria

The stage-gate criteria were defined with the intention to ensure no deterioration in sustainability against both functional units. If the gate requirements are not met, improvements must be made before progressing onto the next step of the evaluation. If major design modifications are needed in order to pass Gates 2, the product must start back again at Gate 1 for evaluation (Figure 8.3, Line A). If the Stage 3 business viability assessment calls for major modifications to the design, the assessment process must start over at Gate 1 to ensure all changes are evaluated for sustainability (Figure 8.3, Line B).

Gate 1: Environmental Assessment

Criteria for Functional Unit A: Performing a comparative LCA between BladeBridge and a conventional bridge, the BladeBridge must demonstrate lower lifetime environmental impacts using a Single Score assessment, and show lower Climate Change impacts.

Criteria for Functional Unit B: Performing a comparative LCA between BladeBridge and utilizing the blade material in cement co-processing, the BladeBridge must demonstrate lower lifetime environmental impacts using a Single Score assessment, and show lower Climate Change impacts.

These calculations were performed in chapter six, and will be replicated in the Data section below.

Gate 2: Social Assessment

Criteria for functional Unit A and B: The s-LCA indicators are founded on socially based SDGs in which Ireland has demonstrated a shortfall, and have been selected based on stakeholders from both customer segments. If the BladeBridge scores a positive number which is higher than both the conventional bridge and utilization of the blade material in co-processing, this indicates the BladeBridge product has the potential to improve Irish performance against socially aligned SDGs. The product assessment can then progress to the next stage.

Phase 3: Business Viability Assessment

At this point in the assessment, the functionally equivalent BladeBridge has been shown to be more beneficial either environmentally, socially, or both as compared to both a conventional bridge and the baseline disposal option for blade material. Because the product has undergone a measurable sustainability assessment, it can now be properly valued for not only its function, but for its potential to contribute to the improvement of sustainability metrics. This measured value should factor into the business viability assessment. Many approaches to assessing business viability can now be used. In this study, an LCC is first done between BladeBridge and (A) a bridge made with conventional materials, and (B) utilizing the material in cement processing. The results of this study were completed in chapter six, and will be replicated in the Data section. The second approach to assess business viability was to undertake interviews according to the I-Corps™ method of customer discovery (Blank and Dorf, 2012) to learn where BladeBridge can add value to stakeholders. A qualitative discussion of these findings is included in the Discussion.

8.3 Data

8.3.1 Gate 1: Life Cycle Assessment

The LCA data will be summarised from chapter six. For more details on the LCA and LCC studies, please refer back to this chapter. To briefly refresh on LCA impact categories which are defined in section 4.2.3, the category of Normalization is calculated by dividing a damage category by the average impact of one European person per year, and Single Score output is the summation of all of the Normalised categories (Humbert et al., 2014). Normalised categories are unit-less and are expressed in ‘Points’ or ‘milli-points’, 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.

8.3.1.1 Functional Unit A: Blade Bridge and Conventional Bridge Comparison

A single score comparison using IMPACT2002+ impact assessment (Humbert et al., 2014) showed BladeBridge as having 14% less environmental impact than a conventional bridge. A second BladeBridge would be slightly improved at 16% lower impact than a conventional bridge due to streamlining the material usage based on learnings from the first BladeBridge (Figure 8.5).

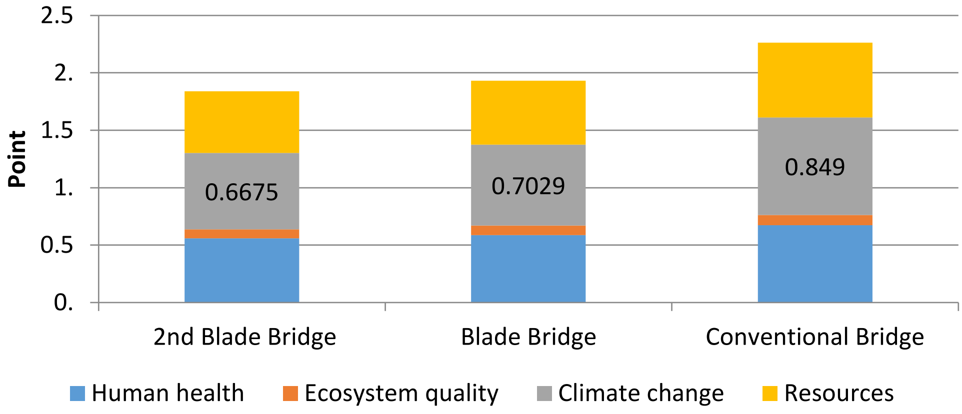


Figure 8.5 Single Score Comparison between blade-bridge and a conventional bridge

The CO_2 emissions of BladeBridge are 17% lower than a conventional bridge. A second BladeBridge would again be slightly improved at 21% lower than a conventional bridge.

8.3.1.2 Functional Unit B: Blade Bridge and Cement Manufacturing

A single score comparison using IMPACT2002+ impact assessment (Humbert et al., 2014) showed the use of the blade material to substitute steel girders in BladeBridge as having 5% less environmental impact than the use of the same material to substitute raw materials and fuel in cement processing (Figure 8.6).

The use of the material in a blade bridge offers 3.3 times the reduction in climate change impact than the use of the material in cement co-processing.

The Gate 1 criteria for Functional Unit A required the BladeBridge to have both lower lifetime environmental impacts, and lower Climate Change impacts than a conventional bridge. These requirements are met.

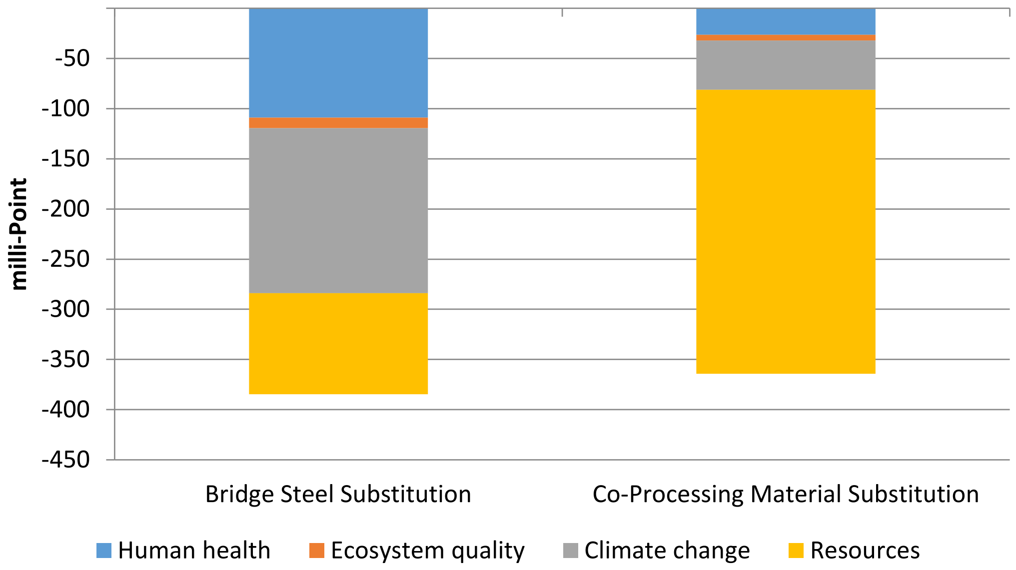


Figure 8.6 Single score comparison of the environmental impacts of utilizing 2250 kg of blade material in a blade bridge and in cement

The Gate 1 criteria for Functional Unit B required the material substitution effects of BladeBridge to have lower lifetime environmental impacts, and lower Climate Change impacts than the material substitution effects of utilizing the blade in cement processing. These requirements were also met. Therefore, the assessment can progress to the Social Life Cycle Assessment stage.

8.3.2 Gate 2: Social Life Cycle Assessment

This section qualitatively assesses the BladeBridge project against the s-LCA indicators established in chapter six. The assessment uses the generic ascending reference scale for social performance evaluation (Benoît Norris et al., 2020) as described in the methodology section, to quantify the assessment. In Table 8.1, the indicator is listed on the left, and the assessment of BladeBridge performance against each indicator is in the middle section. On the right is the assessment number based on the reference scale, per customer segment.

Table 8.1 Comparative s-LCA for BladeBridge including both customer segments

s-LCA Indicator	Assessment	Customer Segment A		Customer Segment B	
		BB	CB	BB	Cement
12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	Re-purposing of blades into pedestrian bridges has the potential to use only 10% of the expected blade material in Ireland (Nagle et al., 2022). Therefore, it is beyond compliance with current regulations, which allow landfill, but will not satisfying the impending requirements of the 2025 landfill ban. Conventional bridges may use recycled steel, which is in line with basic societal expectation. Cement co-processing is not considered recycling, and is therefore below EU compliance levels.	+1	0	+1	-1
12.7 Promote public procurement practices that are sustainable, in accordance with national policies and priorities	BladeBridges include circular material use and reduced environmental impacts, which is beyond current compliance for public procurement. However, the bridges are not zero waste or zero impact, and thus could be improved upon. Conventional bridges are at basic compliance levels. Co-processing of blade	+1	0	+1	0

	material will not help sustainable public procurement.				
12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature	BladeBridge offers sustainable development awareness raising by being visible and tangible in a heavily pedestrianised public setting. It is passively educational, and does not ‘ensure awareness’ but instead offers an awareness raising experience. Publicly repurposing blade material rather than disposing of it is Ideal Performance. Co-processing does not affect this.	+1	0	+2	0
17.14 Enhance policy coherence for sustainable development	BladeBridge allows renewable energy to become cleaner and more circular, thereby improving SDG 7 while preventing a negative knock-on effect on SDG 12. Conventional bridges and co-processing do not affect this.	+2	0	+2	0
17.17 Encourage and promote effective public, public-private and civil society partnerships, building on the experience and resourcing	BladeBridge is an opportunity for county councils and contractors to become educated on the potential for repurposing construction waste, and to upskill their supply chain in this regard. The project will encourage academic, public, private, and civic group collaboration. Conventional	+2	0	+2	0

strategies of partnerships	bridges and co-processing do not affect this.				
	Total	+1.4	0	+1.6	-0.2

From the perspective of customer segment A (public procurers of cycleway bridges), the BladeBridge scores a +1.4 and the conventional bridge scores a 0. From the perspective of customer segment B (wind farm owners with unwanted GFRP blade material), the BladeBridge scores a +1.6 and cement processing scores a -0.2. The BladeBridge scored above 0 and higher than both the conventional bridge and utilization of the blade material in cement processing, passing the Social stage-gate criteria. This indicates that the BladeBridge project has the potential to contribute to the enhancement of performance against the SDGs in some of the socially aligned areas that are most needed in Ireland, and can therefore progress to the business viability assessment.

8.3.3 Gate 3: Business Viability Assessment

In this study, the business viability assessment is not a gate with set requirements. Instead, it is an opportunity to conduct cost comparisons of the alternatives. These appraisals, along with the quantified environmental and social assessments, will assist in further exploring the business case for this product.

8.3.3.1 Functional Unit A: Blade Bridge and Conventional Bridge Comparison

The lifetime cost of the first BladeBridge was 7% more than the conventional bridge, predominantly due to the labour required to reverse engineer the blade. However, a second bridge made using the same blade model can expect to be fabricated at approximately 30% less overall lifetime cost as compared to a conventional bridge (Figure 8.7).

8.3.3.2 Functional Unit B: Blade Bridge and Cement Manufacturing

To recap from chapter six, section *6.3.2.2.2 Market Cost for Co-Processing*, the cost to acquire blades for BladeBridge is €700, the theoretical cost of co-processing of the blade material is €2,628, and the market cost of co-processing is estimated at €10,000 (see Table 6.2). Therefore, the cost of utilizing the blade material in BladeBridge rather than co-processing is somewhere between €1,928 and €9,300. This value could be shared between a BladeBridge business and the wind farm, potentially bringing down the cost of the BladeBridge product to less than the cost of a conventional bridge.

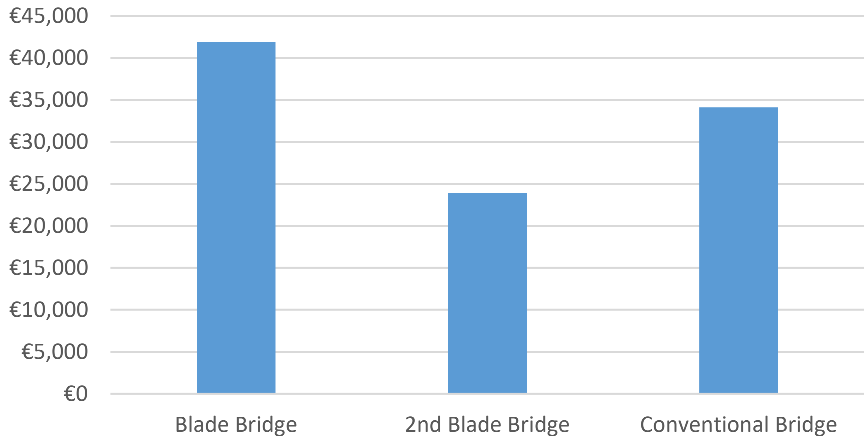


Figure 8.7 Lifetime cost comparison between BladeBridge, a second BladeBridge and a conventional bridge

8.3.3.3 Business Viability Feedback

Once the LCSA was completed, interviews were conducted of many of the identified stakeholders for the BladeBridge project. Business viability feedback fell under three categories:

1. Educating the stakeholders

Industry players such as the County Councils, the Transport Authority, and consultants bidding on cycleway construction must be informed of the life cycle benefits of BladeBridge. An education process must be driven by the BladeBridge team and must include not only information on the structural assessment of the bridge, but also on the environmental and social benefits of the bridge. Conducting this sustainability assessment has given the team this information.

2. Cost reduction

Bridge procurers are increasingly assessing projects based on lowest life cycle cost, rather than acquisition cost. Wind farm owners will begin to be charged more for blade disposal when the landfill ban comes into effect. The LCC comparison that was completed for both of these customer segments shows that BladeBridge can save money for both. BladeBridge could consider entering the market as the less expensive solution for either or both of the customer segments, while the value realisation for the environmental and social benefit is being developed through the educational efforts.

3. Publicity around Sustainable Practices

Several wind farm stakeholders were more interested in the public relations improvements that could be gained by quantifying their reduction in waste or environmental impact. They claimed that they would pay more for this. Having a LCA and s-LCA completed on the BladeBridge to share with stakeholders could help in valuing the total offering.

8.4 Discussion and Conclusions

LCSA aims to provide a broader, more holistic perspective to sustainability assessments, and includes LCA, LCC and the less established s-LCA in its framework. Sustainability assessments can take many forms and have an assortment of end customers. The research presented in this chapter developed an LCSA which can be used in early product and business assessment, to drive innovation in building 'purpose driven businesses.' In this research, socially-focused SDG sub-indicators in which Ireland demonstrated a shortfall were used as the s-LCA criteria. This targeted selection of criteria was intended to drive the development of a product that could help bolster SDG improvement.

The embedded systems model of sustainability was combined with a gate-stage approach to form an LCSA using serial assessments. The product had to pass an LCA based criteria first, as the embedded systems model places the health of the environment as paramount to human and economic health. The second gate was a s-LCA set of criteria that had to be met. Finally, a business viability assessment could be conducted, which is greatly augmented by the environmental and social assessments already completed on the product.

This assessment method showed that the BladeBridge does indeed have the capacity to bolster SDGs 12 and 17 through circular material use, awareness raising, and enhancement of policy coherence, particularly relating to SDG 7 and SDG 12. Sub-indicators 12.5, 12.7, and 12.8 could be improved upon in the BladeBridge project. Performance on sub-indicators 12.5 could be improved by the repurposing of more of the blade material. This could be done both by winning more tenders for BladeBridges, but also by the incorporation of more blade material into each product, such as in a boardwalk design or as use as cross members as well as girders. Incorporating more blade material into each bridge would then improve on indicator 12.7, by potentially reducing the amount of steel material and the associated lifecycle maintenance requirements, and the consequential cost and environmental impacts. The potential for further collaboration with research and private industries has a high potential to boost indicator 17.17.

This framework could be used during any product development, or incorporated into the change control process of existing products. Companies and public bodies could establish Gate Criteria based on corporate, national, or EU targets. Further research could be done to include planetary boundary requirements when calculating the gates, rather than a comparison of existing products.

9 Conclusions

9.1 Introduction

Capitalising on its abundance of wind, Ireland has chosen to meet a target of 70% renewable energy capacity by 2030 through the aggressive growth of its wind energy infrastructure. While this increase in renewables is bringing Ireland closer to achieving the GHG reductions required by the Paris agreement, the development of wind farms is also resulting in an impending end-of-life blade disposal problem that will increase in the coming years. To contribute to the solution, repurposing of the discarded blade material into necessary civic and public structures is proposed, thereby avoiding landfill while simultaneously reducing raw material consumption that would have been required in order to build these structures. In this way, small steps could be made to begin to decouple renewable energy generation in Ireland from the production of waste.

The research in this thesis aimed to answer the overarching question '**Can repurposing of discarded Irish blade material offer overall improvements in sustainability**?' Four sub-questions posed in chapter one supported the exploration of this question, and will be discussed shortly. However, first, the overarching question must be unpacked into implied sub-questions within it.

First, will there in fact be discarded blade material in Ireland? Based on a turbine lifespan of 20 years, the Re-Wind GIS group estimated a cumulative total of nearly 55,000 tonnes of blade material by 2039, peaking at 9,000 tonnes per year around 2037 (Delaney et al., 2021). However, the actual flow of discarded blade material will be based on when the blades no longer offer value to their owner, which could be much longer than the estimated 20 years. Interviews with wind farm owners, the DECC, and industry experts indicate that the industry and the government waste management department see blade waste as an upcoming problem, from both a waste management as well as a public perception perspective.

Next, 'repurposing' must be defined. To separate the efforts of the Re-Wind network from other projects focusing solely on blade recycling, 'repurposing' was clearly defined in section 6.1.3 as "The blade (being) used whole or sectioned into parts and repurposed for other products such as parts of temporary or inexpensive housing, office and home furniture, benches and playgrounds, pedestrian bridges, and power-line structures" (Gentry et al., 2020).

The next implied question is by what are we measuring 'Sustainability'? In this thesis, sustainability was measured using the framework of LCSA, which includes LCA, LCC and s-LCA. LCSA, when proper boundaries are set, can quantify 'overall improvements' by capturing the lifetime impacts and costs across all damage categories within a bounded area and time. Boundaries are established by setting a functional unit. In the case of repurposing blade material into necessary blade products with sellable value, the project has impacts in two areas: (1) Product procurement when the customer is a potential procurer of blade products, and (2) Waste management when the customer is an owner of unwanted blade material. 'Overall improvements' therefore must be assessed based on both customer segments and each of these assessments must then be compared to an established baseline option. Included in this question is whether the blade products are necessary, e.g., are the blade products truly replacing something that would have been built, thereby substituting an amount of raw material that would have been used as well as avoiding the landfill of the material. Or, are the blade products built as a novelty item to simply use up unwanted blades, thereby not actually substituting any material that would have been used, but still avoiding landfill of the material.

Finally, the word 'Can' must be discussed. 'Can repurposing of discarded Irish blade material offer overall improvements in sustainability?' implies more than just LCSA calculations of whether repurposing has the technical potential to offer these benefits. To fully explore the 'Can' question required understanding current and future policy supports such as GPP and the expected landfill ban in 2025, as well as business models which develop value creation for stakeholders within both customer segments. It became clear that to answer this question required a blended exploration of different disciplines through multi- and trans-disciplinary research.

9.2 Thesis in review

This section will review the thesis findings by chapter, illustrating how chapters four through eight contributed to answering the four supporting questions posed in the Introduction.

9.2.1 Chapter four: What are the most likely end-of-life disposal methods for blade material?

In chapter four, the best practice disposal method of Irish blade material was determined to be co-processing in a cement kiln in Ireland, from an environmental perspective as measured using LCA. For the purposes of this research and as a comparative baseline for the remainder of the thesis, this disposal method was set as the environmental baseline against which to compare other end-of-life disposition options. This chapter addressed Q1: *Currently, what are the most likely end-of-life disposal methods for Irish blade material, and what are the environmental impacts of these methods?* However, the research found that the ease of this disposal method combined with the composite industry claim that co-processing is considered ‘Recycling’ (section 4.1) might de-incentivize other disposition options that are further up the Waste Hierarchy. Therefore, the challenge posed in this chapter was the need to develop blade end-of-life solutions that are measurably better both environmentally and economically, that will ensure the option of co-processing in Ireland is passed over for a more sustainable Irish alternative.

9.2.2 Chapter five: What blade repurposing scenarios offer the most environmental gains?

Chapter five used LCA to measure the environmental benefits of repurposing blade material, as utilized in three different scenarios. The scenarios were pieced together by identifying structures that could be made from segments of the wind blade based on congruent shape matching and referencing the Re-Wind Design Atlas (Bank et al., 2018b), and grouping these products together under a public or private end customer segment. Other factors that contributed to creating the scenarios were maximum utilization of the full blade, and the substitution of high embodied materials such as steel and concrete that would have been used in a product. The three scenarios developed were:

Scenario 1 - Rural Package: Culverts, Greenway Bridges, and farm applications (Public & Private)

Scenario 2: Glamping Package (Private)

Scenario 3: County Council Urban Package. Planters, Bus Stops/Bicycle Shelters, bollards (Public)

The scenario that offered the most benefit was the ‘Glamping Package’ due to the use of the blades to replace sheet steel and timber struts for roofing and fencing, and the reduction of transportation impacts due to this business model requirement to transport the blades directly to the glamping site. However, none of the scenarios were calculated to offer more immediate environmental impact reduction than co-processing of the blade material. All of the three scenarios do contain the possibility that the material could be repurposed a second and subsequent time and finally co-processed at end-of-life, and draws the informed assumption that the overall environmental benefits are greater through initial repurposing and then co-processing, rather than co-processing immediately. This chapter began to explore the policy supports and business value creation by critically discussing how much blade material could be reasonably consumed through these scenarios. The estimate that 20% of Irish blade material annually might be able to be used is based on the forthcoming requirement for county councils to adhere to GPP, and an increase in expected demand for glamping facilities initiated by the Covid pandemic. Thus, this chapter addressed *Q2: What blade repurposing scenarios offer the most environmental gains considering the options most likely to be implemented in Ireland based on business demand and policy?*

9.2.3 Chapter six: How would a pedestrian bridge built using discarded wind blades offer life cycle cost, social and environmental improvements (Part 1)?

Chapter six is a case study on one specific product from the scenarios in chapter five – the BladeBridge. This chapter added LCC to the LCA study, to assess hotspots in both cost and environmental impact along the full lifecycle of this product. Thus, it answered the first part of Q4: *How would a pedestrian bridge built using discarded wind blades offer life cycle cost, social and environmental improvements?* This is the first introduction to the idea that blade products have two customer segments and must offer value to both sides. A quantification of the offering for each customer segment also requires the establishment of two different functional units, thereby beginning to blend the engineering LCA work with business considerations. In this study, the first segment is the Wind Farm owner with unwanted blade material, and the corresponding functional unit is 'The disposal of 2.25 tonnes of blade waste for 60 years.' The second segment is a procurer of a pedestrian bridge, and the corresponding functional unit is 'A 22m^2 pedestrian bridge with emergency vehicle load capacity of 12 tonnes, over 60 years.'

A comparative LCA/LCC is completed both against a conventional bridge, as well as against the baseline disposal option of co-processing. In this study, the blade bridge was better environmentally than co-processing and a conventional bridge, less expensive than the estimated costs for co-processing, but slightly more expensive than a conventional bridge. However, second and subsequent BladeBridges made with the same blade model are expected to cost slightly less than a conventional bridge. Additionally, subsidizing the construction of the BladeBridge with blade collection charges from the wind farms would also bring the cost of the BladeBridge down below a conventional bridge. Additional value could be offered to the wind farms in the form of a waste diversion declaration or EPDs. It was the first study to indicate that the BladeBridge could be economically viable, as well as better environmentally from both a waste disposal and a bridge procurement perspective.

9.2.4 Chapter seven: How could social life cycle assessment criteria be developed for assessing new business models in Ireland?

Chapter seven developed a new method for selecting s-LCA for a new product, which can be used independently or as part of a full LCSA. This chapter addressed *Q3: How could social life cycle assessment criteria be developed for assessing new business models in Ireland, considering both national and planetary needs?* In considering the idea of 'thinking global, acting local', the SDGs, which are considered the planet's KPIs, were used. SDGs in which Ireland displayed a 'significant' shortfall were overlaid over the identified socially aligned SDGs, identifying SDGs 2, 5, 12, and 17 as relevant. Sub-indicators from each of these SDGs were then further assessed as relevant to the product being considered, based on a list of collected stakeholders across customer segments. A final list of five sub-indicators remained to serve as the s-LCA indicators. Based on this vetting process, these five indicators are globally and socially relevant, and can offer measurements of areas in which local improvement is most critically needed.

9.2.5 Chapter eight: How would a pedestrian bridge built using discarded wind blades offer life cycle cost, social and environmental improvements (Part 2)?

Chapter eight combined the LCA/LCC results from chapter six with the s-LCA indicators developed in chapter seven to perform a full LCSA. This chapter answered the second part of Q4: *How would a pedestrian bridge built using discarded wind blades offer life cycle cost, social and environmental improvements?* The embedded systems model of sustainability was combined with a stage-gate approach, in which the BladeBridge had to pass first an environmental comparison based on LCA, followed by a social comparison based on s-LCA before being allowed on for a cost assessment of the product based on LCC. Each stage considered both customer segments and both functional units. The results showed that the BladeBridge can indeed offer environmental gains both from a waste diversion and a bridge procurement perspective, as well as offering improvements against SDGs 12 (Sustainable Consumption and Production) and 17 (Partnership for the Goals). The BladeBridge project is suggested as having the potential to help Ireland decouple renewable energy generation from the production of waste.

9.3 Significance of this research

9.3.1 Including LCA in the repurposing debate

LCA based decision making is essential to ensure that environmental gains are truly being made through repurposing. Keeping materials in use is in line with the circular economy, but is not always the most beneficial choice. This research inserts LCA at the forefront of making data based decisions on repurposing discarded material. For example, repurposing of the blade material in scenario 3 of chapter five no longer offers benefits if the material is transported more than 371 kilometres. The choice of whether to repurpose material, when supported with LCA, can help with decision making for companies and governments. These calculations could contribute to the uptake of blade products by customers who are publicly accountable for and are measuring their environmental impacts.

9.3.2 Environmental and cost assessments

This research contains the first LCA comparing blade waste end-of-life options of landfilling to co-processing in a cement kiln, from a waste management perspective. This research contributed to the Wind Europe discussion in support of a European landfill ban. The research went on to correlate customer segments to functional units, in order to assess products made from waste in a combined LCA/LCC approach that could be used to assess any waste repurposing project or product. It demonstrates that the repurposing of blade material in infrastructure projects can offer environmental improvements at a similar cost to the use of conventional material.

9.3.3 Waste diversion declaration

One practical application of this research is the generation of waste diversion declaration. These would be issued to the generators of the waste material, to show that they have now been ‘dispositioned’ to a next life use. It would include an LCA based quantification of the environmental impacts avoided through the substitution of virgin materials with the discarded material. This declaration offers the producers of waste a way to stay more involved in the lifecycle of the material that comes into their possession, sharing in the value created and credit garnered for the end-of-life choices made. This is different than, but could be complementary to, the EPA End of Waste process discussed in chapter two (DCCAE, 2020; EPA, 2020). In the case of blade material that is acquired from a wind farm and transformed into a public structure such as a BladeBridge, a waste diversion declaration would be issued to the wind farm showing the environmental impacts diverted through the substitution of steel girders with blade material.

9.3.4 GPP support and wording for green tenders

The Action Plan on Green Public Procurement (Irish Department of Public Expenditure and Reform, 2021) lists as a key action the exploration of the feasibility of developing a national methodology for life cycle analysis and life cycle costing for publicly funded construction projects. The research in this thesis could contribute to this methodology.

The BladeBridge product could serve as a test product to develop wording around green tendering. The tendering requirements could necessitate LCA based calculations, and include marginal pricing scope based on environmental impact reductions. The quantified environmental, social and cost gains that might be realised through the BladeBridge could help to motivate the authority pre-approval work, such as the Transport Infrastructure Ireland Technical Approval Process, to ensure that this difficult piece of work is resourced properly and completed.

9.3.5 Tool for early business assessment of purpose driven businesses

The novel approach to LCSA based on the embedded systems model of sustainability, along with the SDG based method of s-LCA indicator development, can be replicated for other projects in other regions, and can contribute to forming a research based methodology for early stage planning of ‘purpose driven’ businesses. This method also allows for the quantification of the environmental and social ‘value’ to be included in the overall evaluation of a product from the start.

9.3.6 Job creation implications

The research in this thesis supports the use of discarded materials in repurposing projects as close to their origin as possible. The LCA calculations of chapter five showed that transportation impacts can override the benefits of material substitution in some repurposing scenarios. Several previous studies indicated that job creation through recycling tends to create jobs in more rural areas, which typically have a higher unemployment rate. The local repurposing of blade material would indeed fit this model, as wind farms in Ireland are always quite rural and therefore local repurposing would require rural job creation. Additionally, BladeBridge fabrication would require a new skill set, combining the expertise of a turbine repair technician with that of a bridge fabricator. The creation of this new field, combined with the approach of developing 'purpose driven businesses' as discussed in the previous section, could offer exciting opportunities for innovative rural job creation.

9.3.7 Blade products decoupling renewable energy generation from the production of waste

Finally, Ireland was noted as having a 'profound waste management problem' (Coalition 2030, 2018), and needing to decouple its economic growth from resource consumption. Ireland will be dramatically expanding its renewable energy production by increasing wind energy generation in the coming years, potentially resulting in large amounts of composite waste in the absence of end-of-life blade options. This research shows that repurposing blades could help to decouple renewable energy generation from the production of waste, and sets the stage for repurposing of other C&D waste in support of improving SDGs 12 and 17.

9.4 Reflections and Limitations

At the start of this research, I decided that an environmental 'baseline' for blade disposal must be established against which to compare the repurposing ideas generated by the Re-Wind group. This would ensure that our new repurposing solutions were indeed better environmentally, as measured using LCA, than the end-of-life solution currently, or most likely to be used. Chapter four established this as co-processing of the material in a cement kiln, and calculated the environmental gains offered through the use of the blade material to substitute fuel and raw material for clinker production. Contrary to my expectations, the comparison of the co-processing scenario against the three repurposing scenarios in chapter five showed co-processing to be better than these scenarios. These calculations assumed that the blade material replaces an amount of coal for fuel. Repurposing this material means that it could still be co-processed at its ultimate end-of-life, thereby allowing for more gains. However, at the end of the repurposed life of the product, which could be 60 years, co-processing (if this process exists at all) will almost certainly be replacing a lower or zero impact fuel, and will thus offer less gains through fuel substitution. The gains made through the material substitution would possibly be more beneficial at this point in time. So, is this an argument then to choose co-processing now to provide the most overall and immediate environmental gains? I decided no for the following reasons. My calculations did not take into account that there are plenty of other waste materials that can be used to replace fuel in a cement kiln, and the use of a highly engineered, extremely durable material in this way is likely not the best option. Also, if we rank the abatement of GHGs above all other environmental concerns, two of the three scenarios in chapter five, as well as the BladeBridge, offer more reductions in GHG than the use of the material in co-processing. I chose to not conduct a prospective LCA on end-of-life options in 60 years' time, as I felt it was outside of the scope of this work. Instead, for the BladeBridge, I conducted a study of the bridge for design and construction choices that would enable a wider choice of end-of-life options for the bridge.

The baseline also served for comparisons of impacts due to transportation. As discussed above, use of the blades locally could not only increase innovative jobs in rural locations where they are most needed. It will also keep the impacts due to transportation to a minimum. Enabling communities to use the material that is in their vicinity, reducing transportation impacts, and creating new jobs are all aspects of the importance of considering regional material flow.

The 'substitution of material' approach used in chapters four and five showed what gains could be made through the use of blade material rather than raw material. Estimating the lifespans of each of these products simply entailed looking up the design specifications. For example, bus stops are typically made from polycarbonate, which has a design life of 10 years. A blade with 60 years of expected lifespan would theoretically replace 6 of these products. However, as with the difficulty in estimating a wind turbine lifespan, the true functional lifespan of each of these products is unknown. Likewise, would a bus stop actually be required in 60 years' time at the location it was installed? Will there even be buses in 60 years? The choice of whether to use the design life or an estimated functional life can add uncertainty to calculations. Likewise the BladeBridge design life was set at 60 years, and calculated to directly substitute a conventional bridge. Conventional bridges are typically designed to 120 year design life. Therefore, would it have been more correct to say the BladeBridge offers half of the substitution due to having half the design life? I chose to make their functional life spans the same, as it is more likely that due to climate change and changing modes of transportation, the bridges will be obsolete in 60 years' time, and therefore should have the same lifespan for the purposes of LCA calculations.

Reflecting on the cross-disciplinary efforts in this thesis, the aim was to first understand the difference between multi-, inter-, and trans-disciplinary collaboration, and the importance of each. The second aim was to work towards transdisciplinarity in at least one of the studies in this research, in order to understand the level of learning required and enhancements it offers in answering a research question. I felt that chapter five was the most transdisciplinary of the pieces of work in this thesis, which was conducted only midway through the work. However, for this effort, I found that I was pulling prior work from the Product Design and GIS groups in a 'multi-disciplinary' approach, and then teaching myself aspects of Business Models and Stakeholder engagement, in order to become transdisciplinary in my own knowledge. Therefore, I think transdisciplinary work was achieved within this research, but possibly not transdisciplinary collaboration.

Reflecting on the gaps identified in the literature review, this research contributes greatly to global literature. It includes the first quantitative assessments of the best practice for end-of-life blade disposal, including an LCA comparing co-processing of the blades to landfill and to multiple repurposing options. The research has developed a metric which estimates the amount of carbon emission savings that can be made by replacing hard to abate materials with the use of unwanted blade material. Although our project narrowly missed producing the first ever bridge made from repurposed wind blades, this thesis has delivered the first comparative LCA and LCC of an as-built blade repurposing project. Further novel contributions were made through the use of SDGs to build regionally specific s-LCA indicators. These were combined with the LCA and LCC to build a two-sided LCSA for the assessment of sustainable waste repurposing projects which is entirely novel in both application and methodology.

9.5 Areas for further research

Several research topics could be continued from this study that are specific to decommissioned wind turbine blades. As co-processing of blade material continues to increase, a more accurate assessment of the gains truly being made through the use of blade material, taking into account actual substitution rates, should be made. Ideally, this should support decision making around the extent of the use of co-processing. From a repurposing perspective, other blade products such as sound barriers and transmission towers should be assessed against the LCSA framework in chapter eight, to begin consideration for product development. Blade products and a blade product business could be further assessed using the Doughnut Economics model.

This would entail measuring the products or overall business against planetary boundaries rather than just LCA.

From a wider perspective of repurposing waste material, more work could be done on understanding and tracking regional waste material flow. Policy recommendations for streamlining the End of Waste process so as to make the legal aspects of dealing in waste, reuse and repurposing more affordable for small and medium companies.

From an educational perspective, more research should be conducted on how to incorporate transdisciplinary training into the engineering curriculum, or the modelling of a separate Transdisciplinary Engineering curriculum. Easier to use LCA tools should be developed, and these tools, as well as overall life cycle thinking, should be incorporated into the engineering, architecture, and design curricula.

9.6 Concluding statement

While the topics of LCA and LCSA, wind turbine blade end-of-life options, repurposing of construction waste, and the SDGs have been covered extensively in the literature, the combined application of LCSA and the SDGs to the topic of wind turbine blade repurposing had not yet been conducted. This thesis applies the framework of LCA and LCC to the novel application of the comparison of end-of-life options for wind blade material, both from a waste diversion as well as a repurposing and material substitution perspective. The use of the SDGs to create regionally specific s-LCA indicators, which are then incorporated into an LCSA framework, is a novel methodology. Finally, the use of this LCSA methodology to assess the second only in the world pedestrian bridge built from decommissioning wind turbine blades, is entirely novel in both methodology and application. Although this study was conducted on blade material decommissioned and repurposed in Ireland, the methodology and application are very transferable both to other geographical areas, as well as in other repurposing projects.

With wind energy set to expand rapidly in Ireland and Europe, in the next decade, the methods and proposals outlined here can help to ensure that the life cycle of this industry becomes more circular and contributes to improving national performance against relevant SDGs. The repurposing potential of blade material should be viewed as a quality resource which can offset impacts of necessary public and privately procured infrastructural elements. A business which delivers blade products has the potential to decouple wind energy generation from waste production, thereby moving a key, highly-visible and polarising industry away from its current linear approach.

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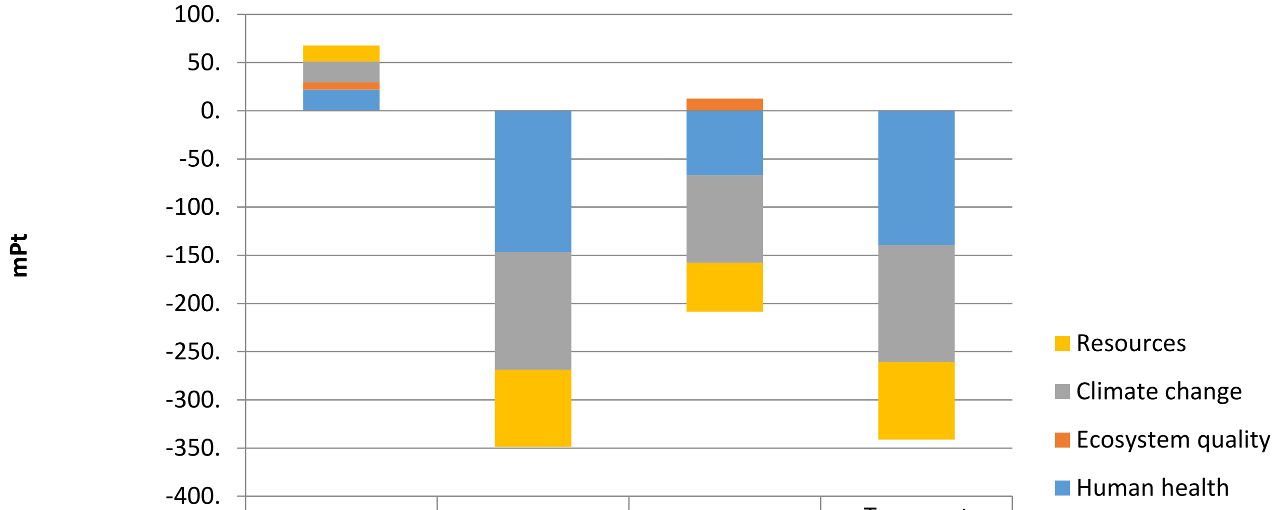
Appendix

Table A.1 Sensitivity Analysis varying the main inputs in the LCA

	Expected Lower Impact	Chosen Value	Expected Higher Impact	Results Summary
Transportation	N/A	Transport, truck 10-20t, EURO4, 100%LF, default/GLO Economic	EURO1	Varying the European Emission standards between the lowest (EURO1) and highest (EURO4) made <2% difference to the single score output for the scenario: 10% Substitution rate with co-processing in Ireland (Figure A.1).
Shipment Type		Container ship ocean, technology mix, 27.500 dwt pay	Transport, barge ship, bulk, 12000t, 100%LF,	Varying the shipping type between container shipping and barge shipping from Ireland to Germany results in

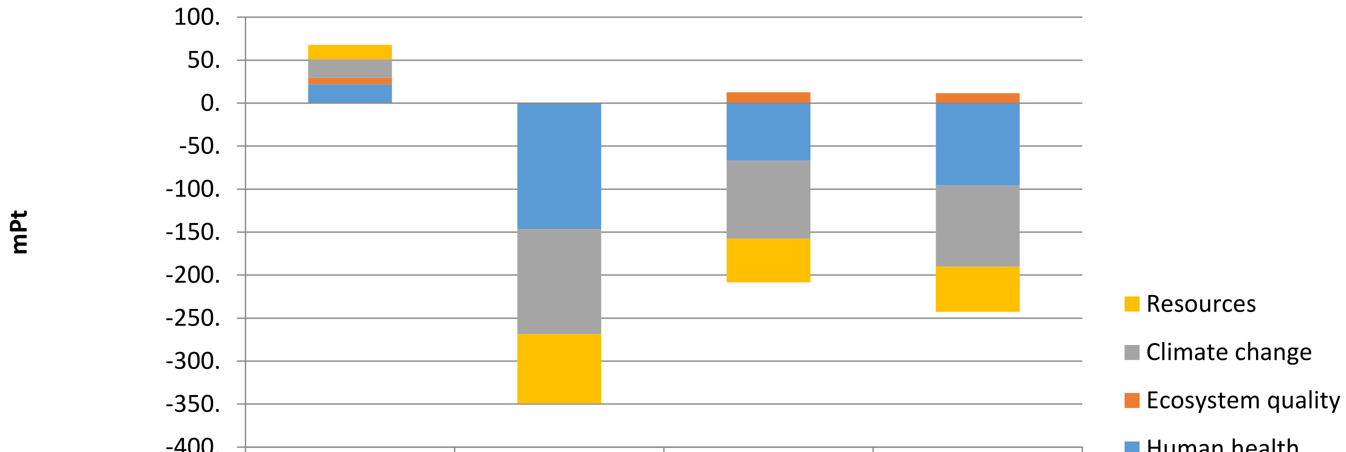
		load capacity RER S	default/GLO Economic	8% more impact when barge shipping for the scenario: 10% Substitution rate with co-processing in Germany (Figure A.2).
Electricity mix IE	N/A (PV not available in Ireland)	Electricity, low voltage {IE}| market for | APOS, S (Irish Electricity mix 2014)	N/A	For Ireland, a national electricity mix calculated in 2014 was available, with no other options.
Electricity mix DE	Electricity, low voltage {DE}| electricity production, photovoltaic, 570kWp rooftop installation,	Electricity, low voltage {DE}| market for | APOS, S (German Electricity mix 2014)	N/A	PV electricity mix is available in Germany, and results in a 12% decrease in impact overall for the scenario: 10% Substitution rate with co-processing in Germany. However, the impact is still less than 10% substitution rate

	multi-Si	APOS, S	with co-processing in Ireland (Figure A.3).



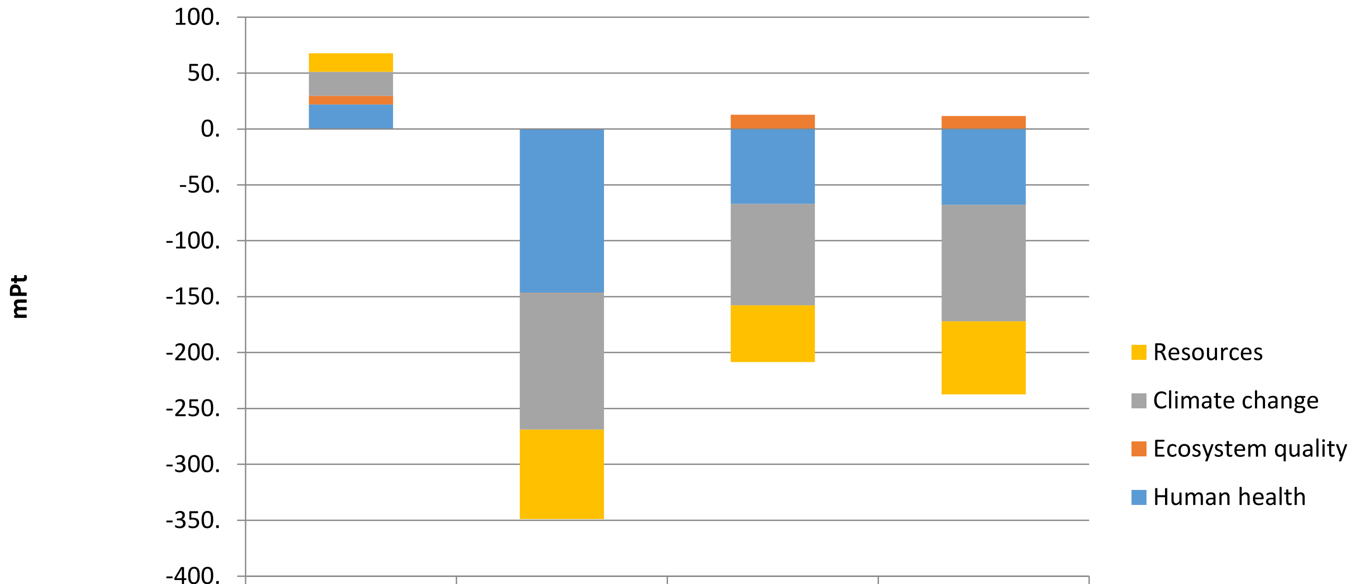
	Blade to Landfill	Co-Process Ireland 10% Subst	Germany 10% Subst	Transport EURO1 Co-Process Ireland 10% Subst
Resources	16.5969	-80	-51	-80
Climate change	21.5708	-122	-91	-122
Ecosystem quality	7.5503		12.6219	
Human health	22.0086	-147	-67	-139

Figure A.1: Transport truck emissions impact on single score output for scenario 2.



	Blade to Landfill	Co-Process Ireland 10% Subst	Germany 10% Subst	Germany 10% Subst Barge ship bulk 100%LF
Resources	16.5969	-80	-51	-53
Climate change	21.5708	-122	-91	-94
Ecosystem quality	7.5503		12.6219	11.641
Human health	22.0086	-147	-67	-96

Figure A.2: Shipment type impact on single score output for scenario 1.



	Blade to Landfill	Co-Process Ireland 10% Subst	Germany 10% Subst	Germany 10% Subst PV Roof
Resources	16.5969	-80	-51	-65
Climate change	21.5708	-122	-91	-104
Ecosystem quality	7.5503		12.6219	11.6935
Human health	22.0086	-147	-67	-68

Figure A.3: Electricity mix impact on single score output for scenario 1.

Table A.2: 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	2	High interest; pilot project underway in 2021; med-high utilization of blade waste; GPP; steel substitution	4-high

			for blade utilization for greenway bridges			
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	3		4-high

			incorporated into Glamping application			
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	GPP, Good use of offcuts; steel or plastic substitution; low fabrication requirements	3-med-high
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	1,2,3	Possibility of utilizing offcuts from other projects in this application, to	3-med-high

			for greenways and public spaces		consume parts that might go to landfill; steel substitution	
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	2-med

					barrier; potential high utilization; GPP; steel substitution	
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 usable.	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	Public, low to med quantity blades utilized, engineering would be difficult	1,2, (3?)	Low utilization, one off project. Likely unpopular	1-low
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	N/A	N/A	N/A	N/A	0-N/A

	than repurposing					
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

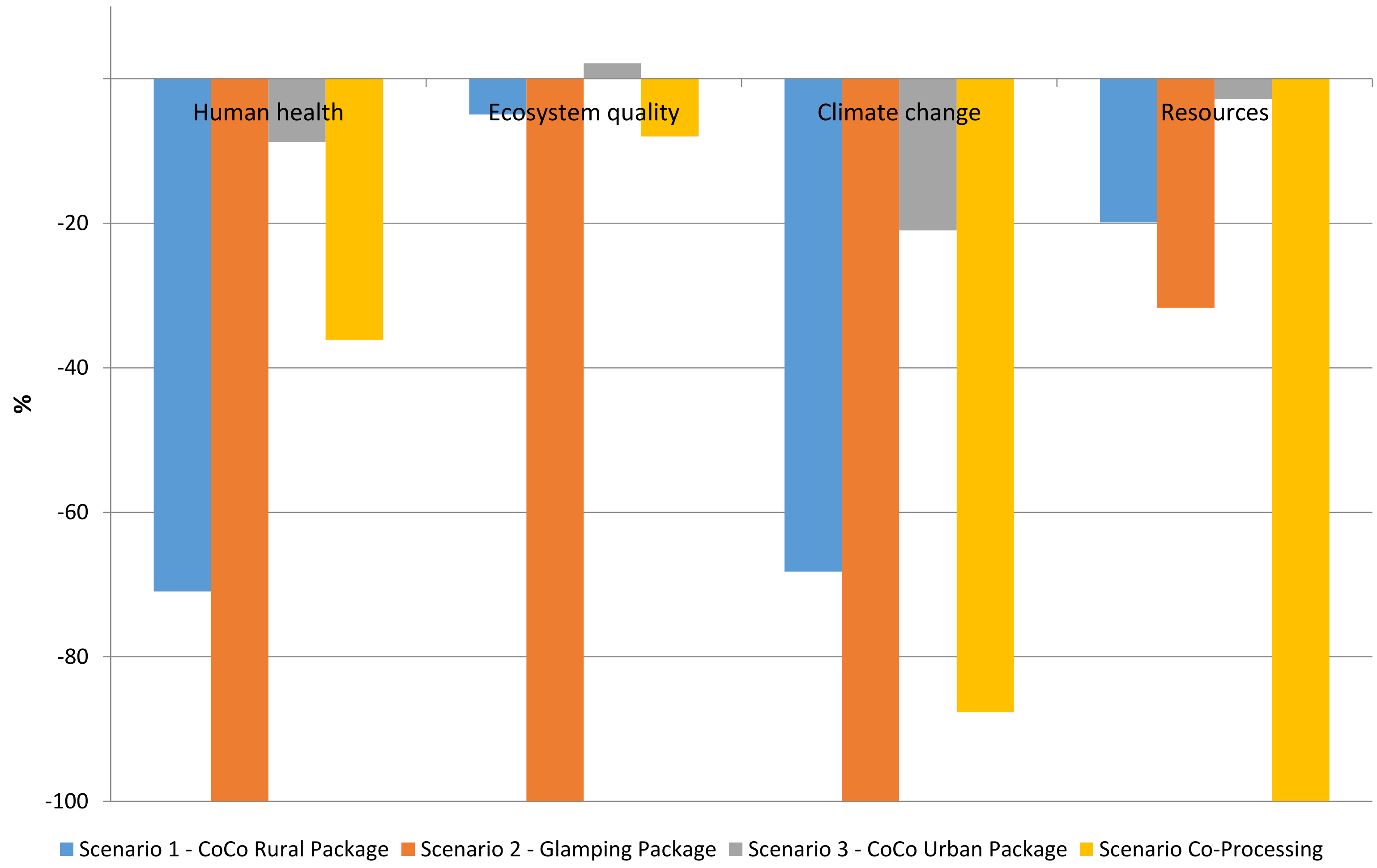


Fig. A.4: Damage Assessment comparison of three scenarios and co-processing

Table A.3: Bill of materials (BOM) for both bridge designs for each module. Amounts are representative of the full lifecycle and for the bridges as a whole. The amounts for modules B1–B8, C1–C4 and D were calculated based on the scenarios presented in Table A.4

Bridge	**Module**	**Resource**	**Qty**	**units**
	A1-A3	Cross beams (203x133x25); Galvanised Steel with recycled content	820	kg
	A1-A3	Support Beams (50x50x6); Galvanised Steel with recycled content	38	kg
	A1-A3	Steel decking (1.5mx2m sheets); Galvanised Steel with recycled content	1628	kg
Both	B2	Anti-graffiti coating every 5 years @ 5kg each coat	55	kg
	C1	Fully electrified deconstruction	No Impact	
	C2	Fully electrified transport to recycling centre 200 km away	No Impact	
	C3	100% steel recycling, 90% concrete crushing and reincorporating into new foundations	Outside boundary	
	A0	Oven type SNOL Model 12/1100, 30 hours @800C, would equal 1.5kW * 30 hours	45	kWh

	A1-A3	FRP End Caps	25	kg
Blade	A1-A3	Connectors, bolts, cradles; Galvanised Steel with recycled content	609	kg
Bridge	A1-A3	Parapets; Stainless Steel	289	kg
	A2	3 * 0.75 tonne Blades transported 432 km from Everun to MTU	972	tkm
	A3	2983 kg of Steel transported 1316 km by road and 126 by ferry from Luxembourg	3926	tkm
	A5	Concrete Abutments at tip & root; C40/C50 50% GBBS	0.6	m3
	A5	Formwork; plywood	0.1	m2
	B2-B3	Painting Steel Surfaces ever 20 years and 40 years @26kg per 2 coats	52	kg
	C3	90% FRP recycling for 45% GF replacement	Outside boundary	
	A1-A3	Conventional Bridge Girder (376x151x51 S355); Galvanised Steel with recycled content	561	Kg
Conventional	A1-A3	Connectors, bolts, cradles; Galvanised Steel with recycled content	609	Kg

Bridge	A1-A3	Parapets; Stainless Steel	0.077	m3
	A3	3656 kg of Steel transported 1316 km by road and 126 by ferry.	4811	tkm
	B2-B3	Painting Steel Surfaces ever 20 years and 40 years @32kg per 2 coats	64	kg
	C3	100% steel recycling	Outside boundary	

Table A.4: Common maintenance scenarios, and estimated end-of-life scenarios for both bridge designs

Bridge	**Module**	**Resource**
Both	B2	Bridge fully resurfaced at 30 years. Same quantity of epoxy resin and bauxite aggregate applied as during initial construction
	C1	Fully electrified crane and construction vehicles
	C2	Fully electrified transport to recycling centre 200 km away
	C3	100% steel recycling, 90% concrete crushing and reincorporating into new foundations

	C4	10% landfill of concrete and FRP
BladeBridge	B2	Anti-graffiti coating every 5 years @ 5 kg each coat
	C3	100% steel recycling, 90% concrete crushing and reincorporating into foundation, 90% FRP recycling for 45% GF replacement
Conventional Bridge	C3	100% steel recycling

Table A.5 Assessment of 47 SDG sub-indicators

List of SDGs Categorised as 'Social' in which Ireland has a Major or Significant Challenges	Applicable Blade Bridge Stakeholders
2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round	No
2.2 By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons	No
2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment	No
2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality	No

2.5 By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed	No
2.a Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development and plant and livestock gene banks in order to enhance agricultural productive capacity in developing countries, in particular least developed countries	No
2.b Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round	No
2.c Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including on food reserves, in order to help limit extreme food price volatility	No
5.1 End all forms of discrimination against all women and girls everywhere	No
5.2 Eliminate all forms of violence against all women and girls in the public and private spheres, including trafficking and sexual and other types of exploitation	No
5.3 Eliminate all harmful practices, such as child, early and forced marriage and female genital mutilation	No

5.4 Recognize and value unpaid care and domestic work through the provision of public services, infrastructure and social protection policies and the promotion of shared responsibility within the household and the family as nationally appropriate	No
5.5 Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic and public life	No
5.6 Ensure universal access to sexual and reproductive health and reproductive rights as agreed in accordance with the Programme of Action of the International Conference on Population and Development and the Beijing Platform for Action and the outcome documents of their review conferences	No
5.a Undertake reforms to give women equal rights to economic resources, as well as access to ownership and control over land and other forms of property, financial services, inheritance and natural resources, in accordance with national laws	No
5.b Enhance the use of enabling technology, in particular information and communications technology, to promote the empowerment of women	No
5.c Adopt and strengthen sound policies and enforceable legislation for the promotion of gender equality and the empowerment of all women and girls at all levels	No
12.1 Implement the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries	No

12.2 By 2030, achieve the sustainable management and efficient use of natural resources	Yes (but Included in LCA)
12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses	No
12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment	Yes (but Included in LCA)
12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	Yes
12.6 Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle	No
12.7 Promote public procurement practices that are sustainable, in accordance with national policies and priorities	Yes
12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature	Yes

12.a Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production	No
12.b Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products	No
12.c Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities	No
17.1 Strengthen domestic resource mobilization, including through international support to developing countries, to improve domestic capacity for tax and other revenue collection	No
17.2 Developed countries to implement fully their official development assistance commitments, including the commitment by many developed countries to achieve the target of 0.7 per cent of gross national income for official development assistance (ODA/GNI) to developing countries and 0.15 to 0.20 per cent of ODA/GNI to least developed countries; ODA providers are encouraged to consider setting a target to provide at least 0.20 per cent of ODA/GNI to least developed countries	No
17.3 Mobilize additional financial resources for developing countries from multiple sources	No

17.4 Assist developing countries in attaining long-term debt sustainability through coordinated policies aimed at fostering debt financing, debt relief and debt restructuring, as appropriate, and address the external debt of highly indebted poor countries to reduce debt distress	No
17.5 Adopt and implement investment promotion regimes for least developed countries	No
17.6 Enhance North-South, South-South and triangular regional and international cooperation on and access to science, technology and innovation and enhance knowledge-sharing on mutually agreed terms, including through improved coordination among existing mechanisms, in particular at the United Nations level, and through a global technology facilitation mechanism	No
17.7 Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favourable terms, including on concessional and preferential terms, as mutually agreed	No
17.8 Fully operationalize the technology bank and science, technology and innovation capacity-building mechanism for least developed countries by 2017 and enhance the use of enabling technology, in particular information and communications technology	No
17.9 Enhance international support for implementing effective and targeted capacity-building in developing countries to support national plans to implement all the Sustainable Development Goals, including through North-South, South-South and triangular cooperation	No

17.10 Promote a universal, rules-based, open, non-discriminatory and equitable multilateral trading system under the World Trade Organization, including through the conclusion of negotiations under its Doha Development Agenda	No
17.11 Significantly increase the exports of developing countries, in particular with a view to doubling the least developed countries' share of global exports by 2020	No
17.12 Realize timely implementation of duty-free and quota-free market access on a lasting basis for all least developed countries, consistent with World Trade Organization decisions, including by ensuring that preferential rules of origin applicable to imports from least developed countries are transparent and simple, and contribute to facilitating market access	No
17.13 Enhance global macroeconomic stability, including through policy coordination and policy coherence	No
17.14 Enhance policy coherence for sustainable development	Yes
17.15 Respect each country's policy space and leadership to establish and implement policies for poverty eradication and sustainable development	No
17.16 Enhance the Global Partnership for Sustainable Development, complemented by multi-stakeholder partnerships that mobilize and share knowledge, expertise, technology and financial resources, to support the achievement of the Sustainable Development Goals in all countries, in particular developing countries	No

17.17 Encourage and promote effective public, public-private and civil society partnerships, building on the experience and resourcing strategies of partnerships	Yes
17.18 By 2020, enhance capacity-building support to developing countries, including for least developed countries and small island developing States, to increase significantly the availability of high-quality, timely and reliable data disaggregated by income, gender, age, race, ethnicity, migratory status, disability, geographic location and other characteristics relevant in national contexts	No
17.19 By 2030, build on existing initiatives to develop measurements of progress on sustainable development that complement gross domestic product, and support statistical capacity-building in developing countries	No