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Article

Evaluating the environmental dimension of material efficiency strategies relating to the circular economy

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Abstract: Material efficiency is a key element of new thinking to address the challenges of reducing impacts on the environment and of resource scarcity, whilst at the same time meeting service and functionality demands on materials. Directly related to material efficiency is the concept of the Circular Economy, which is based on the principle of optimising the utility embodied in materials and products through the life cycle. Whilst steel, as a result of high recycling rates, is one of the most 'circular' of all manufactured materials, significant opportunities for greater material efficiency exist, which are yet to be widely implemented. In the field of Life Cycle Management, Life Cycle Assessment (LCA) is commonly used to assess the environmental benefits of recovering and recycling materials through the manufacturing supply chain and at end-of-life. As well as containing information to calculate environmental impacts, LCA models also provide the flows of materials through the product life cycle and can also be used to quantify material efficiency and the circularity of a product system. Using an example taken from renewable energy generation, this paper explores the correlation between product circularity and the environmental case for strategies designed to improve material efficiency. An LCA-based methodology for accounting for the recovery and re-use of materials from the supply chain, and at end-of-life, is used as the basis for calculating the carbon footprint benefits of five material efficiency scenarios. Resulting carbon footprints were then compared with a number of proposed material circularity indicators. Two conclusions from this exercise were that i) LCA methodologies based around end-of-life approaches are well placed for quantifying the environmental benefits of material efficiency and circular economy strategies and ii) when applying indicators relating to the circularity of materials these should also be supported by LCA studies.

Keywords: Life Cycle Assessment, Circular Economy, Material Efficiency, Recycling, Reuse

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1. Introduction

The increasing demand by society for services and infrastructure (e.g. transport, energy, buildings) and the need to address environmental issues such as greenhouse gas emissions and resource consumption delivers a tension that is a fundamental challenge of the current time. Concepts such as Material Efficiency and the Circular Economy (CE) aim to address this challenge largely through the principle of delivering the same or greater functionality currently provided by materials, whilst using fewer resources. Much of the focus is on product-based strategies such as greater product durability and design of products to enable enhanced recovery of materials (including for recycling and reuse) at the end of product life [1-5].

As these strategies are developed, modelled and tested, a simplified indicator of material efficiency or of material circularity may be a useful dimension within product design tools. However,

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an important questions which shouldn't be overlooked when seeking greater material circularity is that of what is worth recovering, and what is recovery worth? In other words, it is important that material efficiency strategies are also evaluated carefully in the environmental dimension, so that informed and optimal decisions about product design, service delivery and new business models can be made.

Such environmental evaluations can be well made by adopting the principles of life cycle thinking and more specifically Life Cycle Assessment (LCA), a modelling technique by which the environmental impacts of a product or service over the full life cycle are quantified, with a principal aim being to avoid shifting burdens between different phases of the life cycle or between different environmental impact categories.

Many materials are vital in enabling transport, energy generation and much of the other functionality required by current and future society. It is therefore incumbent upon the materials sector to explore with urgency the strategies needed to deliver the functionality required of it in the most material efficient manner. Whilst the materials and manufacturing industries, for reasons of their own business sustainability, pursue initiatives on circular economy and material efficiency [6-8], often relating to their products downstream of manufacture, there remain many opportunities to explore and develop further.

The question of how to quantify, attribute the benefits and identify opportunities in Circular Economy strategies such as refurbishment and product system re-use is one of significant methodological debate, yet a number of tools already exist or are under development for this purpose. Case studies are often a useful way to illuminate answers to such research questions and to inform future strategies, design decisions and business models. In this paper, several of the existing tools for the assessment of material circularity, together with an LCA-based method, have been tested and compared using an example from the renewable energy sector.

1.1. Qualitative and quantitative tools for measuring material efficiency

A number of tools exist for the assessment of product level material efficiency. These tools vary in complexity and methodology, from very simple qualitative tools to complex methods almost resembling full Life Cycle Assessment. The aim of such tools is to inform life cycle design decisions without the need for a full study.

Two summaries of material efficiency tools were recently published [9,10]. Based on these two publications, a collection of eight material efficiency measurement tools was assembled, as given in Table 1.

Table 1. Material Efficiency assessment tools, as described by Linder [9] and Saidini [10].

Tool Name	Author / Date	Focus	Output
Material Circularity Index (MCI)†	Ellen MacArthur Foundation / Granta Design 2015	Reuse / Recycling	Numerical
Eco-Costs†	Vogtländer et al 2001/2012	Economics	Numerical
Circular Economy Index	Di Maio 2015	Economics	Numerical
REPRO2	Gehin 2008	Remanufacturing	Guidance
C2C	Ecolabel Index	Materials & Use	Guidance
Economic Value Ratio	Linder 2017	Economics	Numerical
Circular Economy Toolkit†	Evans 2013	Materials & Use	Graphical
Circular Economy Indicator Prototype†	Cayzer 2016	Materials & Use	Graphical & Numerical

For the purposes of this study, four of the tools highlighted in Table 1 (identified by †) were selected and were applied to a case study to allow comparison with a full Life Cycle Assessment tool. Details of the tools selected are given in later sections.

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1.2. Evaluating material efficiency strategies using life cycle assessment

Material Efficiency strategies can be applied along the complete life cycle of a product. The manufacture, use and finally end-of-life of products all have some aspect of material efficiency associated with them. This is also the case for the circular economy, where material efficiency strategies have been evaluated through the use of indicators, which are directly linked to material flows across the product life cycle. Examples of such indicators include: product life span, reuse rates and recycling rates. The common, underlying feature of circular economy indicators is that they typically focus on improving resource efficiency by diverting material away from landfill or incineration. Whilst there is often a strong connection between resource efficiency and indicators relating to reuse or recycling it is less clear how such indicators correlate with wider environmental impacts. This is particularly the case where activities such as refurbishment, remanufacture or recycling are energy intensive when compared to the manufacture of the initial product. In addition, for scenarios based around extended product life there are also potential trade-offs between environmental impacts in manufacture and durability. For example, a more durable engineering component might require greater processing in manufacture, leading to an increased environmental burden associated with production, but less over the whole life cycle when the benefits of extended use are accounted for.

In order to answer questions such as what is the environmental benefit of recycling, reuse or extending product life, and therefore what is worth recycling, reusing or maintaining in a circular economy, there is a strong argument for using environmental assessment methods such as LCA to evaluate different scenarios.

When developing an LCA study to evaluate scenarios relating to the circular economy, it is important to consider the system boundary of the study. A conventional system diagram, which includes manufacture, use and end-of-life disposal (a 'cut-off' approach) typically does not account for the upstream or downstream environmental burdens of recovered materials that cross the system boundary and are utilised by other products or processes. An effective LCA therefore needs to have an extended system boundary, considering processes and products beyond the first life cycle, in order to evaluate each potential scenario.

LCA has been widely used for characterising the environmental benefits of recycling and organisations such as World Steel Association have recommended methods that can be used to evaluate the benefits of recycling steel products. Such approaches provide a useful starting point for evaluating scenarios relating to the circular economy and this paper explores how they can be further developed and applied not just to scenarios relating to recycling but also to reuse and extended product life.

1.2.1. Terminology

E The LCI parameter or article relating to entire product life cycle after accounting for recycling and reuse

E_{man} The LCI parameter or article relating to manufacture of a product containing a proportion of recycled content (R_1)

E_v The LCI parameter or article relating to 100% primary production.

$E_{recycle}$ The LCI parameter or article relating to 100% secondary production

E_{reuse} The LCI parameter or article relating to refurbishment for reuse

R_1 The proportion of recycled content, which is used in manufacturing the product

R_2 The recovery rate of material at end-of-life, which is recycled

n Number of times the product is reused before disposal or recycling.

Y The efficiency, or yield, of the secondary production process

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1.2.2. Accounting for recycling

When steel is recycled, it is remelted into steel which can be used in any product application, regardless of its origin, so steel that once was in a building can be recycled and used to make a car, a drinks can, or another building. This means that steel flows in open loop recycling systems, since the steel flows in different product loops. ISO 14044 [11] states that *a closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.* Previous work [12] has applied this principle to calculating the benefits of steel recycling, which forms the basis of the recycling methodology adopted by the World Steel Association [13]. Using the definitions described in the previous section an equation can be developed to account for either material that is recycled at end-of-life or for recycled content (the use of recyclate during manufacture).

$$E = E_{man} - (R_2 - R_1)Y(E_v - E_{recycle})$$

1.2.3. Accounting for reuse and refurbishment

Steel reuse differs from recycling in that rather than the product being returned to a steel manufacturing site, for remelting, the product is used again in the same or other application. If the product is used again for the same application then reuse can also be considered as an extension of product life. In some instances, it may be necessary to repair or refurbish the product before it is suitable for reuse. Reuse can therefore have multiple facets and approaches for modelling each possible scenario, within an LCA, will depend on the functional unit and the goal and scope of the study.

In this paper, the example of a tidal energy device is used to illustrate an approach for accounting for reuse. The functional unit considers an installation, which is in operation for a period of 100 years and during this time-frame different scenarios are considered for reuse and extending the life of parts. The reused parts remain within the foreground system boundary which differs from the parts that are destined for recycling. Material sent for recycling could enter a variety of different product systems and is therefore considered as part of the background system (Figure 1). Equally, recycled material used in manufacture could have originated from any number of different end-of-life products.

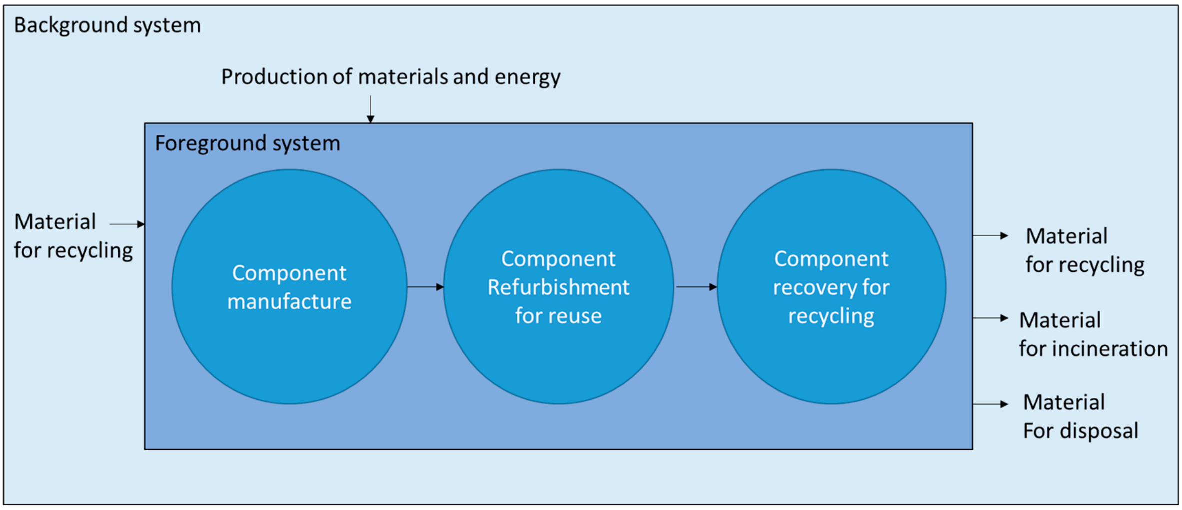

Figure 1. Foreground and background system for a product that is reused and then recycled.

In the situation where the functional unit includes both the original part and any subsequent reuse and refurbishment activities, the following equation can be developed:

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$$E = E_{man} + nE_{reuse} - (R_2\text{-}R_1)Y(E_v\text{-}E_{recycle})$$

2. Evaluating material efficiency strategies: A case study

In order to study the effectiveness of different material efficiency strategies, a case study was conducted based on a prototype tidal energy device. A tidal energy device is a renewable energy system designed to extract energy from the ebb and flow of tides in offshore areas with high tidal flow speed [14]. The development of tidal stream power is currently at an earlier stage than more common renewable energy sources such as wind power, and a wide range of designs exist, though many of the most successful devices are of the three-blade horizontal axis type. Such devices are generally seabed-mounted and many designs at first glance resemble a wind turbine, though due to the relative densities of water and air, a tidal turbine has a much smaller rotor diameter than that of a similarly-rated wind turbine. Tidal turbines are often rated at 1-2MW, and are envisaged to be installed in arrays conceptually similar to wind farms, of the order of 100s of MW. The development of the first such arrays is currently underway off the coast of the UK, for example the MeyGen array, which aims to install 398MW of tidal generation capacity by 2020 [15].

The prototype device used for the comparative study was a 1MW rated device. For the purposes of this study it was divided into three distinct sections: firstly a 'device' section comprising the steel turbine body, internal electronic components and yaw rotation system, secondly a 'support' section comprising the support structure, mounting system and foundations, and finally the composite turbine blades ('blades'). In this case, the support structure was manufactured entirely of steel, and the mounting system was a steel and concrete piled foundation system. The tidal turbine is illustrated in Figure 2.

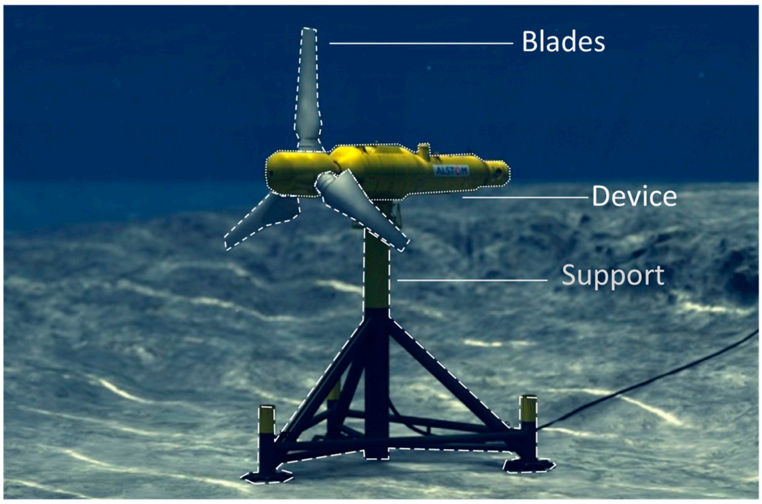

Figure 2. Case study prototype Tidal Turbine parts: Device (Blades & Body) and Support (Support Structure & Mounting). Foundations not shown.

By mass, the turbine device comprises approximately 52% mild steel, 35% stainless steel, 11% iron and 2% copper. The support structure comprises 60% mild steel and 40% cementitious materials, and the blades are entirely made of composite materials.

In order to compare different material efficiency assessment methods, five cases were defined. The boundary of the study was defined by a functional unit, which specifies the number of products and number of product lifetimes included in the study. A functional unit of 10MW of rated power over 100 years was used in all cases. The prototype device has a design life of 25 years and is rated at 1MW, so four installations of ten devices are required to meet the functional unit.

A 'business as usual' case was initially established. In this case, the device and support would be replaced together after 25 years. In the business as usual case, current levels of recycling were assumed [16], with no recycling or energy recovery from composite or cementitious materials). From

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this initial case, four further cases were developed. Cases were developed in which device and support lifetimes were extended to 50 years by either refurbishment after 25 years, or by life extension. In the former case, the carbon emissions from the removal, refurbishment and re-installation of the support were included in the carbon footprint study, and where possible in the material efficiency tools. A summary of the cases developed is given below, and the functional unit as satisfied by each case is illustrated visually in Figure 3.

- Case 1: Business as usual recycling at end-of-life after 25 years of operation.
- Case 2: As Case 1 with additional energy recovery from blades at end-of-life.
- Case 3: Support is refurbished and reused after first 25 year lifetime. Recycling and energy recovery as Case 2.
- Case 4: Support lifetime is extended to 50 years. Recycling and energy recovery as Case 2.
- Case 5: Support lifetime is extended to 50 years. Device is refurbished and reused after first 25 year lifetime. Recycling and energy recovery as Case 2.

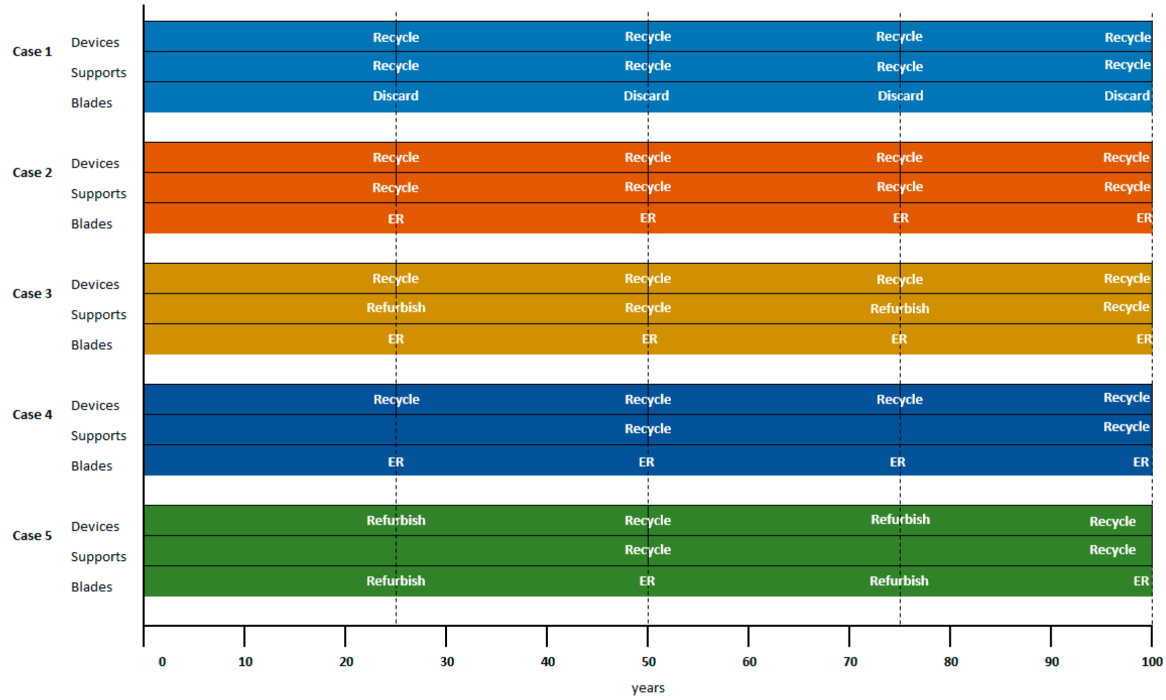

Figure 3. Illustration of the five life cycle cases used in case study.

A zero recycling case, in which no recycling took place and each device and support was discarded and replaced at the end of each 25 year lifetime, was also studied in some cases. For each of these five cases, results generated by a series of material efficiency tools were compared to the results of a carbon footprint assessment. Four of the material efficiency tools highlighted in Table 1 were selected for this comparison, namely Material Circularity Index (MCI) [17]; Eco-Costs [18]; Circular Economy Toolkit (CET) [19]; and Circular Economy Indicator Prototype (CEIP) [20]. These four methods were selected as they give a broad representation of the range of tools available, both in focus and complexity. The MCI and Eco-Costs tools are numerical calculation methods, with the former focussing on environmental circularity and the latter on economic circularity. The CET and CEIP are simpler, graphically-based tools. The CET is the simplest considered in this study: Its output is simply a recommendation of areas of the development and use of a product which may offer the greatest potential for circularity improvements. The CEIP is a more complex tool, resulting in an assessment of product circularity as a percentage value.

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2.1. Case Study Results: Material efficiency tools

2.1.1. MCI

The Material Circularity Indicator (MCI) method developed by Granta Design is a spreadsheet based tool. Six inputs are required: The reused material percentage, recycled material percentage, recycling efficiency at manufacture and end-of-life stages, and the product lifespan and functional unit relative to industry averages.

For each case, reuse and recycling was calculated at a material level, then the product lifespan multiplier was used to represent reuse and extension of life in the relevant cases. This was applied to each material in the product, then aggregated based on mass proportion to give a case total. The following MCI results were calculated:

- Case 1: 0.439
- Case 2: 0.439
- Case 3: 0.579
- Case 4: 0.635
- Case 5: 0.652

2.1.2. Eco-Costs

The Eco-costs method was originally proposed by Vogtländer [21], and subsequently updated in 2012. Eco-costs are defined as *costs required to reduce the environmental pollution and materials depletion of a product to a level in line with the maximum carrying capacity of the earth*. Carrying capacity is itself defined as the maximum number of individuals of a given species that can be supported on a sustainable basis, in this case meaning a sustainable global human population.

The tool used in this study was that developed alongside the IDEMAT 2015 dataset by Vogtländer et al [22]. In order to represent the five cases, an aggregated approach was used based on the combination of virgin (i.e. non-recycled) and secondary (i.e. recycled) material content for each material, over each 25-year period. In cases 3, 4, and 5, the Eco-costs method is unable to account for the differences between refurbishment and life extension, so any additional resource use due to refurbishment processes was not taken account of.

Three versions of the Eco-costs calculation were undertaken, for three end-of-life scenarios. The first (Landfill) assumes that material waste is sent to landfill at the end-of-life, the second (Open Loop, OL) assumes that material is processed in a modern municipal waste treatment system with metal recycling and heat recovery from plastics. The final (Closed Loop, CL) assumes that used products are returned to the manufacturer and reused in new products. In all cases the Eco-costs value gives the monetary value required to reduce the environmental pollution and material depletion to a level in line with the carrying capacity of the earth. It should be noted that this method was also unable to account for energy recovery from composite materials, so cases 2, 3, 4 and 5 assume the use of virgin composite materials in blade manufacture, as per case 1. Results of the Eco-costs method are given in Table 2.

Table 2. Eco-costs material efficiency tool results for scenarios 1-5 and no recycling.

Case	Eco-costs (Landfill) €	Eco-costs (CL) €	Eco-costs (OL) €
No recycling	12,263,465.60	10,333,819.60	2,846,119.20
1	7,094,842.10	5,165,196.10	2,846,118.42
2 (no ER)	7,094,842.10	5,165,196.10	2,846,118.42
3 (no ER)	5,438,494.50	4,438,797.30	2,119,719.62
4 (no ER)	5,438,494.50	4,438,797.30	2,119,719.62
5	4,408,858.30	3,444,035.30	1,423,059.34

2.1.3. CET

This tool asks the user questions in seven categories, incorporating design and manufacture, materials, use, and end-of-life treatment and uses these to give recommendations for areas of potential improvement. The majority of the 33 answers were identical for each of the five cases, but three questions were answered differently for different cases. These questions related to the percentage of recycled material used (where a variation between case 1 and all subsequent cases was seen); product lifetimes (where a variation between cases 1 and 2, and 3, 4 and 5 was seen); and end-of-life treatment by the manufacturer (where a variation between cases including refurbishment and those without refurbishment was seen).

The output of the CET is a diagram highlighting areas of low, medium, or high potential for improvement in circularity. The results for each of the five cases are given in Figure 4. As can be seen, the tool highlights potential for additional recycling in case 1, but does not suggest any difference in the improvement potential of the remaining four cases, proposing an improvement in refurbishment and remanufacture in all cases.

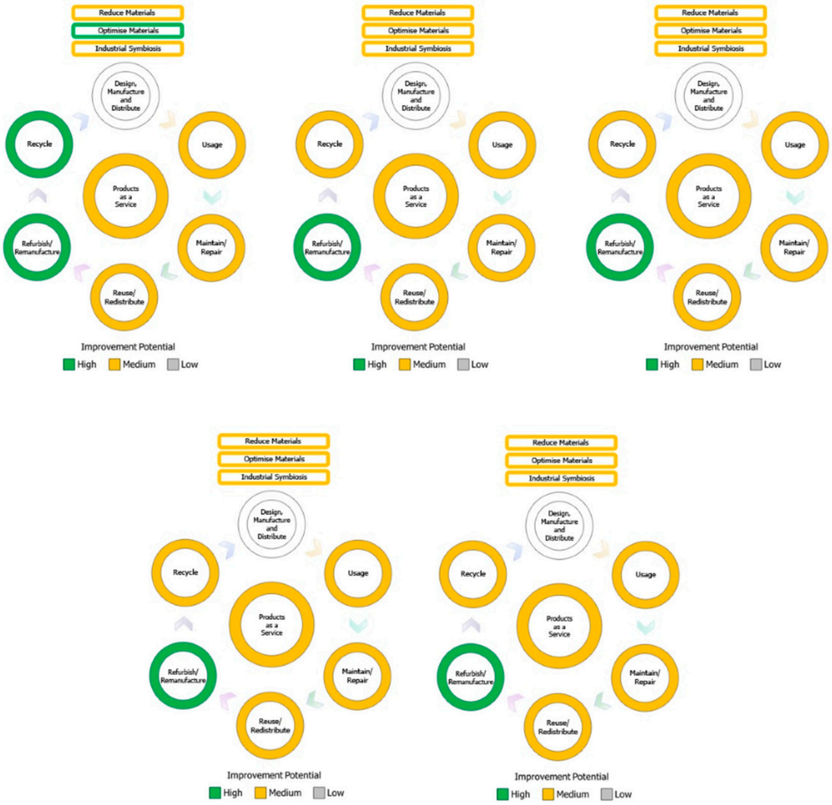

Figure 4. Results of CET material efficiency toolkit (Top: case 1, case 2, case 3. Bottom: case 4, case 5).

2.1.4 CEIP

This tool is spreadsheet-based, and uses the respondent's answers to 15 questions about product manufacture, use and end-of-life treatment to produce a 'Circularity Rating', defined as a percentage value. The tool states that the questionnaire *intends to evaluate in what degree the product fosters the Circular Economy principles throughout its different lifecycle stages*.

The questions cover five topic areas: Design, Manufacture, Commercialisation, Use, and End-of-life, giving 15 questions in total. Answers to 13 of the 15 questions were identical for all cases, with only the first and last questions being answered differently. These questions respectively ascertain the percentage of the product manufactured from recycled or reused material, and the percentage of the product recycled after use, or reused. In all cases it was necessary to aggregate multiple scores for

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products at different stages of the functional unit. The data used to answer these two questions across the five scenarios is as follows:

- Case 1: 70% recycling and 0% reuse at manufacture, 70% recycled and 0% reused at end-of-life (The tool allows the user to select these values with a resolution of 10%. Since recyclable materials actually represent 70.66% of the complete product, a slight error is introduced due to this).
- Case 2: 80% recycling and 0% reuse at manufacture, 80% recycled and 0% reused at end-of-life (again, a slight error is introduced since plastic makes up 9.55% of total mass).

In cases 3, 4 and 5 the device and support are considered separately.

- Case 3: The device is recycled as in cases 1 and 2. To represent the reuse of the support, the first lifetime is modelled as having 80% recycled material at manufacture, and 20% recycled / 80% reused at end-of-life. The second lifetime is modelled with 20% recycled / 80% reused at manufacture, and 80% recycled material at end-of-life. The third and fourth lifetimes repeat this process.
- Case 4: Since the tool is unable to account for the difference between reuse and life extension, cases 3 and 4 are identical.
- Case 5: As in case 3, reuse was represented by linking the reuse at end-of-life of lifetimes 1 and 3 with the reused input to lifetimes 2 and 4. In this case, this method was applied to the device and support.

Aggregated results for the functional unit in each case give the following results, with the resulting graphical results breakdown given in Figure 5.

- No recycling: 44%
- Case 1: 53%
- Case 2: 56%
- Case 3: 56%
- Case 4: 56%
- Case 5: 60%

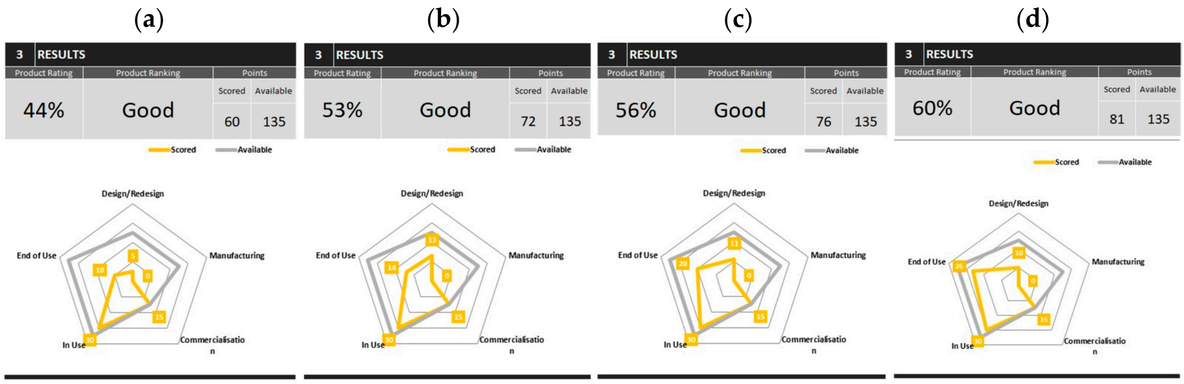

Figure 5. Results of CEIP material efficiency toolkit: (**a**) no recycling case; (**b**) case 1; (**c**) cases 2, 3 and 4; (**d**) case 5.

2.2. Comparison of Material efficiency tools

Direct comparison of the four selected material efficiency tools is challenging, since all give results in their own preferred format. However, in the case of those giving numerical results (MCI, Eco-costs and CEIP), it is possible to normalise these results across the five cases to allow a direct comparison. Results of these three tools, normalised by the case 1 value of each across the five cases, are illustrated in Figure 6.

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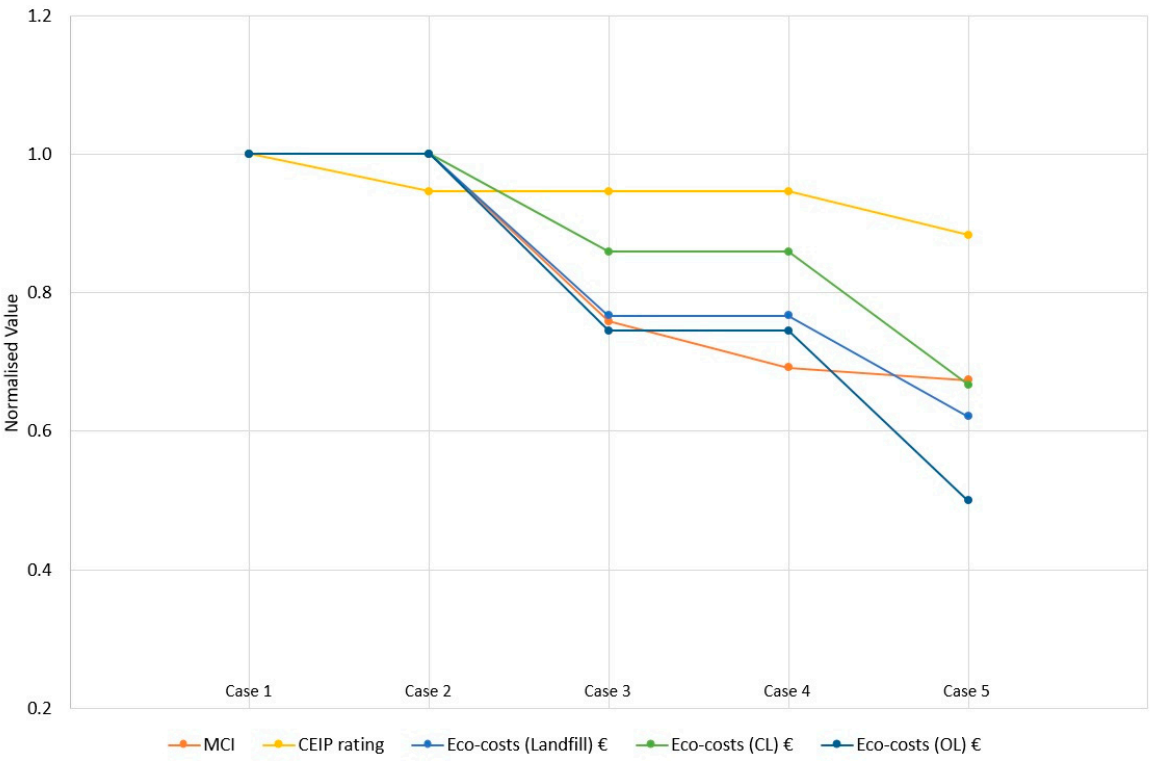

Figure 6. Comparison of normalized results of MCI, CEIP and Eco-costs material efficiency tools.

As can be observed in Figure 6, the trends of the MCI and Eco-costs tools were found to be similar between cases one and three. Both methods were not able to resolve the difference between cases one and two (i.e. the introduction of energy recovery from composite materials), but the MCI method did show a difference between all other cases, whereas the Eco-costs method did not show any variation between cases three and four (i.e. the change from a support structure refurbished after 25 years to one with a 50 year lifetime). The results of the CEIP method follow a slightly different trend. Although this method was able to account for the introduction of energy recovery in case two, it was unable to distinguish between cases two, three and four, to which it attributed the same score.

In order to further assess the strengths and weaknesses of each method, results were subsequently compared to those of a carbon footprint assessment, as introduced in the next section.

2.3 Case study results: Carbon Footprint Assessment

In order to compare the results of the material efficiency tools described in previous sections, a full carbon footprint study was conducted for the Tidal turbine case study. A spreadsheet tool developed specifically for this study was used, and the energy requirement and carbon footprint of each process required to manufacture and install the turbine was calculated. Material production, part manufacture, transport, installation, maintenance and end-of-life decommissioning and recycling were included, with additional calculations of the energy required to refurbish parts in the relevant cases, as well as their associated transport, removal and re-installation requirements. Data was gathered from a range of sources, including tidal turbine manufacturers [23, 24], previous studies [25], and work in other fields (for example, transport sector data was used to establish the fuel consumption and energy requirements of transport by road and sea).

3. Results: Comparison of Material efficiency tools and Carbon Footprint Assessment

Results generated by the three material efficiency tools with numerical outputs (the CET tool produced only a graphical output, meaning we were unable to include its results in further comparison) were compared to those of the carbon footprint study.

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Results from the carbon footprinting tool, in terms of normalised tonnes of CO_2 emissions per functional unit, are compared to the results of the material efficiency measurement tools described previously, in Figure 7.

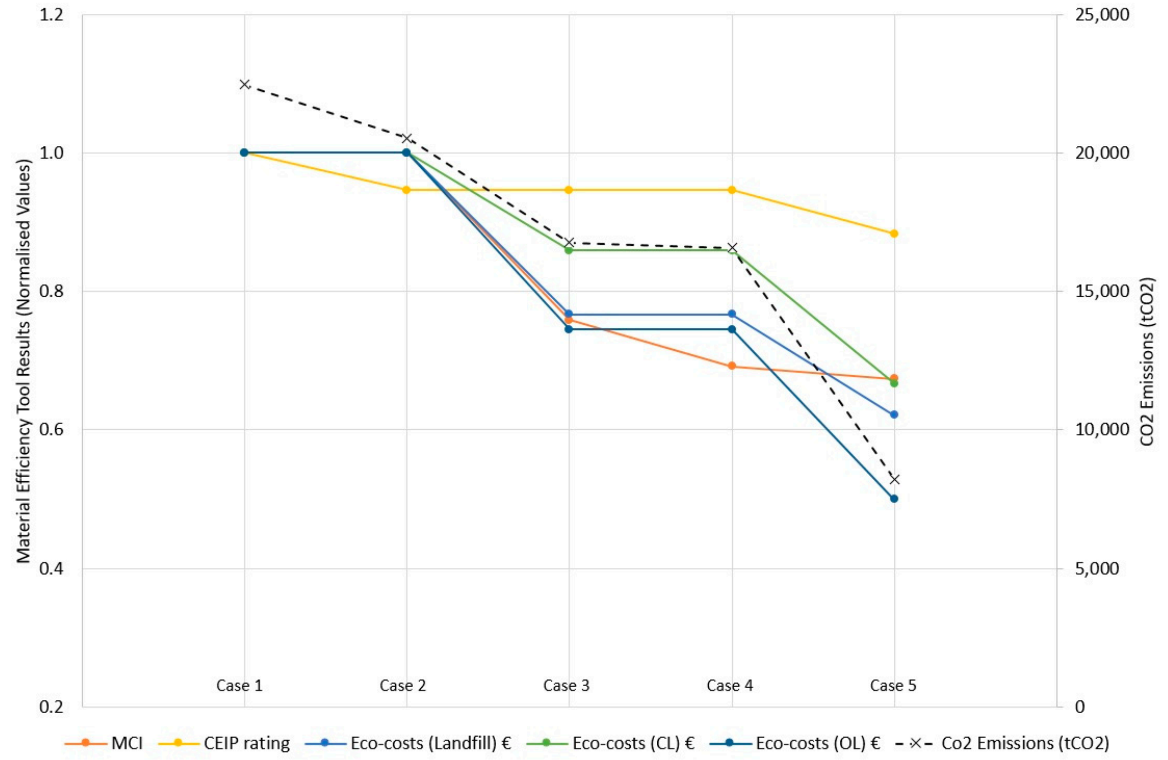

Figure 7. Comparison of material efficiency tools results and carbon footprint study results for Tidal Turbine case study.

It can be seen from these results that the best performing of the three material efficiency tools appears to be the Open Loop Eco-costs measure, but it is evident that all three material efficiency tools struggled to identify the true CO_2 emission benefits of cases two and five. In case two, the reduction in carbon footprint resulting from the use of energy recovery from the incineration of turbine blades at end-of-life was not accounted for by the Eco-costs and MCI measures, which overestimated the CO_2 result by 8.5% compared to the carbon footprint tool. The CEIP tool did account for this change, but still underestimated the benefit by 3.4%.

The reuse of the turbine body and blades in case five was not correctly accounted for by any of the material efficiency tools, resulting in a CEIP error of 58%, MCI error of 46%, and Eco-costs errors of between 27% and 45%. This change resulted in a significant reduction in carbon footprint, and highlights the fact that although material efficiency tools are a relatively quick way to estimate the circularity of a product or process, these tools can lead to different conclusions to those of full analysis, and without the use of a full carbon footprint study it may not be possible to understand the implications of all changes, such as in this case between life extension and refurbishment.

4. Concluding Remarks

Material efficiency and the circular economy are key elements of new thinking to address the challenges of reducing impacts on the environment and of resource scarcity, whilst at the same time meeting the service and functionality demands required by society of materials. Many new strategies and business models for greater material efficiency and circularity are being proposed and developed, however it is not necessarily the case that all of these will lead to a net environmental benefit. Therefore, an environmentally-based assessment of strategies should be carried out in order to understand the (potential for) improvement. Several assessment tools are available and a selection have been tested alongside an LCA-based method, in order to understand the degree to which conclusions arrived at using the different approaches correlate and support good decision-making. In conclusion:

- The circular economy supports the hierarchy of reducing resource consumption, reusing, remanufacturing and recycling materials.
- Policies and methods for evaluating the circularity of the products should not be limited to simple indicators (e.g. rates of recycling or recycled content).
- LCA methodologies based around end-of-life approaches are well placed for quantifying the environmental benefits of material efficiency and circular economy strategies, such as reuse and refurbishment.
- Initiatives relating to the circular economy should make use of the tools and methods that the LCA community have developed to validate the environmental credentials of new products and business models.
- Material efficiency tools can provide useful information on the implications of material use choices, but the method of calculation and inbuilt assumptions of a given tool can have a significant effect on the result.
- When applying indicators relating to the circularity of materials these should also be supported by LCA studies.

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