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SELECTION OF ENVIRONMENTAL SUSTAINABLE FIBER MATERIALS FOR WIND TURBINE BLADES - A CONTRA INTUITIVE PROCESS?

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ABSTRACT

Over the recent decades biomaterials have been marketed successfully supported by the common perception that biomaterials and environmental sustainability de facto represents two sides of the same coin. The development of sustainable composite materials such as blades for small-scale wind turbines have thus partially been focused on the substitution of conventional fiber materials with bio-fibers. The major question is if this material substitution actually, is environmental sustainable. In order to assess a wide pallet of environmental impacts and taking into account positive and negative environmental trade-offs over the entire life-span of composite materials, life cycle assessment (LCA) can be applied. In the present case study, four different types of fibers (carbon, glass, flax and carbon/flax mixture) are compared in terms of environmental sustainability and cost. Applying one of the most recent life cycle impact assessment methods, it is demonstrated that the environmental sustainability of the mixed carbon/flax fiber based composite material is better than that of the flax fibers alone. This observation may be contra-intuitive, but is mainly caused by the fact that the bio-material resin demand is by far exceeding the resin demand of the conventional fibers, and since the environmental burden of the resin is comparable to that of the fibers, resin demand is in terms of environmental sustainability important. On the other hand is the energy demand and associated environmental impacts in relation to the production of the carbon and glass fibers considerable compared to the impacts resulting from resin production. The ideal fiber solution, in terms of environmental sustainability, is *hence* the fiber composition having the lowest resin demand and lowest overall energy demand. The optimum environmental solution hence turns out to be a 70:30 flax:carbon mix, thereby minimizing the use of carbon fibers and resin. On top of the environmental sustainability assessment, a cost assessment of the four fiber solutions was carried out. The results of the economical assessment which turns out to not complement the environmental sustainability, pin-point that glass fibers are the most effective fiber material.

1. INTRODUCTION

The purpose of the present case study is to perform a screening LCA facilitating benchmarking of four different wind turbine blade types, with the aim of illuminating the environmental sustainability performance of bio-composites such as flax based composites and bio-based resin relative to conventional composites such as carbon and glass fiber epoxy based composites.

The dominating industrial and scientific focus on bio-based composite materials (Müssig 2010; Pickering 2008; Mohanty, Misra, Lawrence 2005) are mainly concerned with the technical performance of the materials, but the sustainability of these new materials needs to be addressed as well. The study at hand addresses the environmental issues by presenting the results of a quantitative comparative sustainability assessment of four prototype small-scale wind turbine blades differing only in type and amount of fiber reinforcement material, i.e. conventional and bio-based and/or in the type of resin, a conventional epoxy resin and a bio-based epoxy resin. All blades were designed for being used in a wind turbine car concept (Gaunaa, Øye, Mikkelsen 2009).

Quite a number of LCAs on wind power technology have been published over the last two decades. LCAs of wind power technologies found in the existing literature most often focuses on the comparison of the environmental burdens of different life cycle stages of a wind turbines and/or comparison of complete turbines of various sizes (Davidsson, Höök, Wall 2012). Many of these studies highlight the fact that blades are one of the most environmental burdensome parts of a wind turbine. Still LCAs on wind turbine blades are rare.

A few publications involving comparative LCAs of various blade types or bio-based composites for blades have been identified. One of the most recent publications addressing LCA of materials for blades focuses on the application of nano-carbon for reinforcement (Mergula, Lowrie, Khana, Bakshi 2010). A further “grey” literature publication focuses on the application of bamboo for the blades (Xu, Qin, Zhang 2009). These two publications are as far as we know the only publications assessing the environmental performance of wind turbine blades applying LCA.

As conventional reinforcement, a typical carbon fiber fabric was selected, and as bio-based reinforcement, a commercial flax fiber fabric was selected. Both fiber fabrics were impregnated with a bio-based epoxy resin with “typical” mechanical properties, but sourced from bio-waste. In a previous study, a full technical documentation was done of the mechanical properties of the three composite materials combinations: carbon/epoxy, flax/epoxy and hybrid carbon/flax/epoxy composites (Bottoli, Pignatti 2011). From this, finite element models were constructed to dimension the small-scale wind turbine blades. Manufacturing was done using vacuum infusion to ensure high quality and reproducibility corresponding to industrial standards.

Initially a comparative LCA was carried out (Markussen, Birkved, Madsen 2013) and based on this assessment it was concluded that further analysis and inclusion of glass fiber reinforcement (currently the most used reinforcement for wind turbine blades) was needed in order to evaluate the environmental trade-offs between carbon and flax fiber reinforcement in the hybrid blade. To assess these scenarios a mechanical modeling approach was applied.

2. METHODS

The product system model was set-up in GaBi 4.4 (PE 2011a), and built based on readily available commercial unit processes from either the GaBi professional database (PE 2011b) or the Ecoinvent database (Swiss Centre for LCI 2011). The parameterized model is illustrated in Fig. 1. The product system model covers all relevant life cycle stages of the blade's life cycle from extraction of raw materials, such as crude oil for the epoxy resin, to fuels for waste disposal (here incineration with energy recovery) of the blades. The experimental input for the model are the material quantities consumed during manufacture of the blade prototypes.

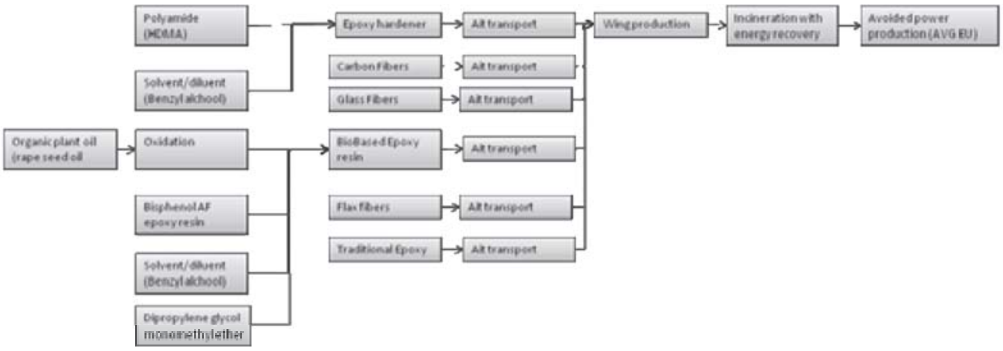

Fig. 1: Product system model.

Due to lack of experimental data, a sequence of assumptions had to be made in order to quantify the composition of both the resin and the hardener. Further explanation of these assumptions and the allocations needed to develop the product system model are presented in Markussen et al. (2013). All estimation work relating to model construction and model parameterization is by the authors considered to reflect the actual conditions as well as possible, and hence are the uncertainties relating to the estimation work and assumptions as low as possible. It is important to keep in mind that the uncertainties relating to the estimation work are approximately equally large for all blade type scenarios, and hence are the overall ratios between the impact potentials of the blade types therefore considered to have a considerable lower uncertainty than the absolute impact potentials (i.e. many of the uncertainties being the same for all blade types, will equal out by the comparison).

In a comparative LCA the same functional unit is used. In the present case study, all the blades have to meet the same stiffness requirements. For the first three scenarios (carbon, flax and hybrid 50/50) a full mechanical analysis of the blades was performed (Bottoli, Pignatti 2011); however, for the glass and the hybrid blades with mixing ratios different than 50:50, no mechanical analyses have been performed.

To obtain the same stiffness of the blades, the Ashby's methodology was used (Ashby 2011). This material selection methodology allows varying the material of an object maintaining the design requirements. In this case, the blade was compared to a beam in order to have a deflection less than the maximal deflection constrain and minimizing the mass. These design requirements are the same as those used to perform the mechanical analysis. The resulting masses serve as inputs for the product system model.

In this case, the Ashby's material index is: $I = \frac{E^{1/2}}{\rho}$ (1)

Hence to obtain the mass of a glass fiber blade with the same flexural stiffness as the other blades, the following equation was used.

$$m_g = \left(\frac{E_r}{E_g}\right)^{1/2} \frac{\rho_g}{\rho_r} m_r \qquad (2)$$

where E (GPa) is the elastic modulus of the material, ρ (g/cm^3) is the density and m (g) is the mass of the blade. The subscript r is referring to the reference material, while g is referring to the glass composite blade. The calculation has been performed with both carbon and flax blades as reference material. The results are presented in Table 1. In order to evaluate the accuracy of the applied mechanical model, the 50:50 carbon:flax blade scenario is evaluated to avoid that large errors are introduced due to the applied mechanical performance assessment approach.

Table 1: Mechanical performance evaluation results of the “pure” composite materials (materials with only one fiber type).

Material	E (GPa)	ρ (g/cm^3)	Mass, real (g)	Mass, calculated (g)
Glass	38	1.88		495 (f) 500 (c)
Carbon	100	1.50	246	243
Flax	20	1.25	454	458

The results obtained for the flax and the carbon blade indicate that no large error is introduced using this simple mechanical performance assessment approach. To obtain the mass of the glass fiber needed on the inside of the composite, the law of mixture was used, assuming a fiber volume fraction (V_f) of 0.50.

The same approach was applied to calculate the weight of the hybrid composite blades with different flax fiber contents (Table 2).

Table 2: Weight of the hybrid blades, and weight of the fiber and resin demands.

% of flax fiber	Blade mass (g)	Carbon fiber mass (g)	Flax fiber mass (g)	Epoxy mass (g)
0 %	246	155	0	91
10 %	257	139	15	103
20 %	270	124	31	115
30 %	283	109	47	128
40 %	299	94	63	142
50 %	316	80	80	157
60%	337	65	98	174
70%	361	51	118	193
80 %	389	35	140	214
90 %	424	18	166	240
100 %	453	0	191	263

For the assessment of the environmental impacts induced by the different blade designs, the ReCiPe Life Cycle Impacts Assessment (LCIA) methodology was applied (Goedkopp et al. 2013). ReCiPe is within the LCA community considered to be one of the most recent and complete LCIA methodologies (Markussen et al. 2013). In the present case study, the Hierarchical assessment perspective is used, since it is the assessment perspective representing an “average political orientation”.

This ReCiPe methodology allows for assessment both on midpoint and endpoint level. In this study, the results are presented at endpoint level or as aggregated endpoints in the form of single score combining all the endpoint categories.

3. RESULTS

The product system model assessment results are presented in Figs. 2 and 3.

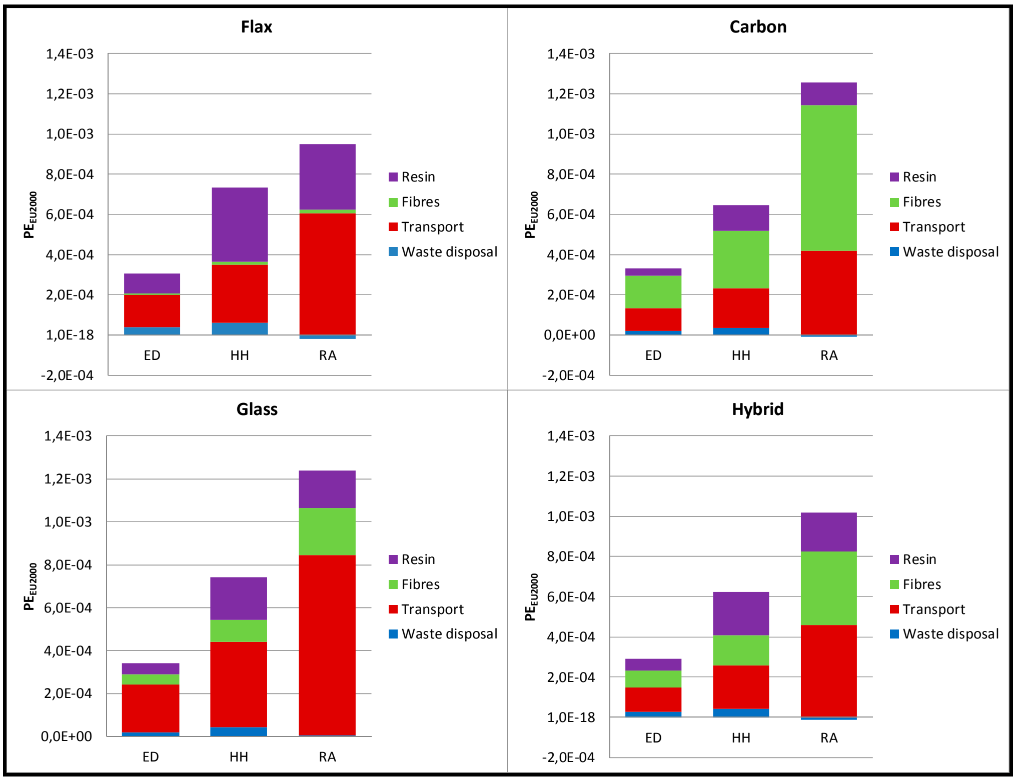

Fig. 2: Impact assessment results at endpoint level for all blade types obtained applying the ReCiPe impact assessment methodology on each blade alternative, applying the Hierarchist result assessment perspective, presented according to product system activity ED = Ecosystem damage, HH = Human Health damage, RA=Resource depletion damage.

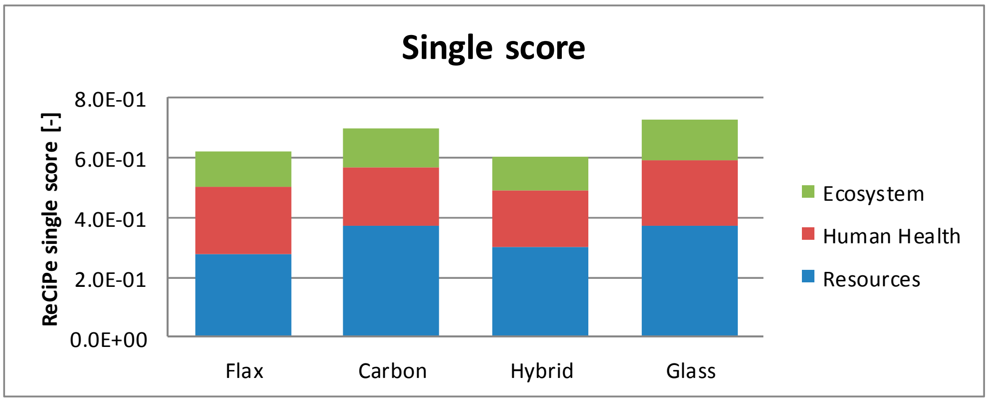

Fig. 3: Impact assessment results on endpoint level for all blade types obtained applying the ReCiPe impact assessment methodology on each blade alternative, applying the Hierarchist result assessment perspective.

In order to illustrate the differences between the bio-based blades and the glass fiber blade, in terms of their contributions to the specific endpoint or single score, the results are also presented in Δ-LCA result form. According to the Δ-LCA result interpretation approach, only the differences in impacts are highlighted, by calculating the differences in contributions to impact categories as:

$$\Delta IP_i = IP\left(flax/hybrid\right)_i - IP\left(glass\right)_i$$

where ΔIP_i is the difference of the specific endpoint impact category, and IP_i is the endpoint impact category of the specific blade scenario.

The results of the Δ-LCA between bio-based and glass fiber blades are presented in Fig. 4. For further in-depth information about the Δ-LCA and the carbon and flax blades, see Markussen et al. 2013.

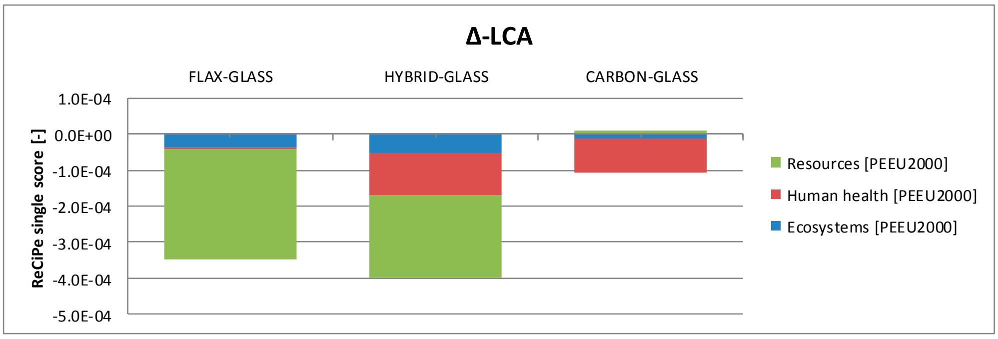

Fig. 4: Impact assessment result difference on endpoint level for all blade types obtained applying the ReCiPe methodology on each blade alternative, applying the Hierarchist result assessment perspective.

The environmental performance of the hybrid blade varies according to the amount of flax fibers applied. The results on the hybrid blade assessment are presented in Fig. 5.

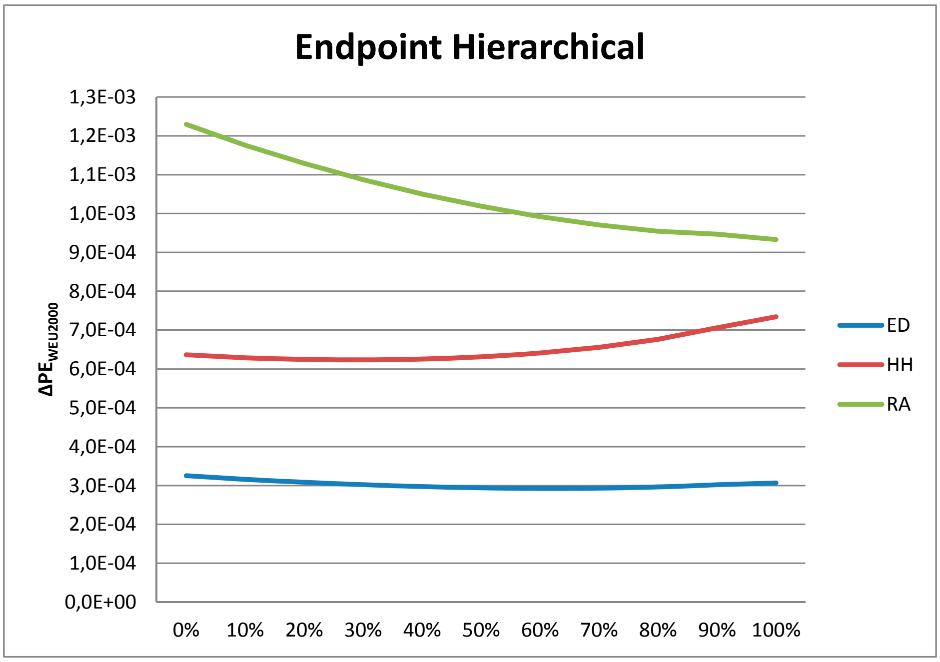

Fig. 5: Impact assessment result for the hybrid blade applying different flax contents on midpoint level obtained applying the ReCiPe impact assessment methodology on each blade alternative, applying the Hierarchist result assessment perspective.

The impacts from different fiber ratios of the hybrid blade are presented in Fig. 6.

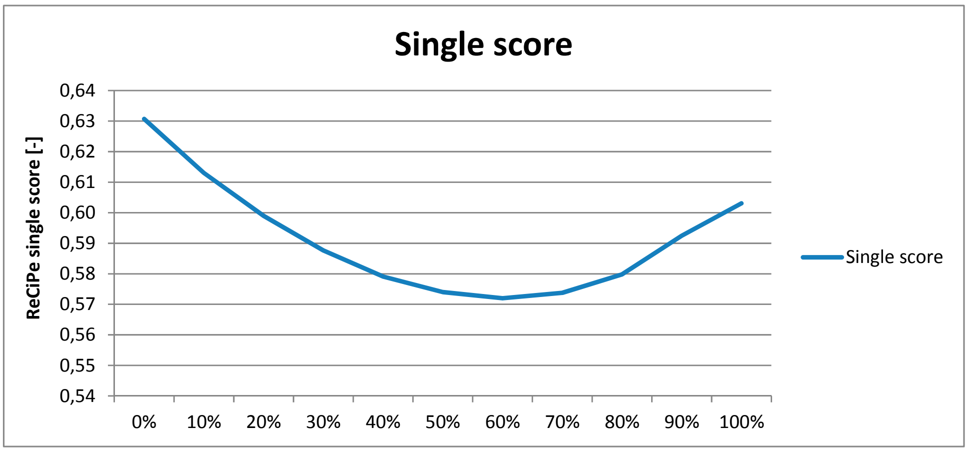

Fig. 6: Impact assessment result for the hybrid blade applying different flax contents on single score level obtained applying the ReCiPe impact assessment methodology on each blade alternative, applying the Hierarchist result assessment perspective.

In Fig. 7, the prices/costs of the hybrid blades are presented applying different fiber ratios. The material prices originate from Bottoli and Pignatti (2012), and are related to the prototype scale. Although the prices do not represent the true price in an industrial massive scale production, the prices are considered representative on a relative scale.

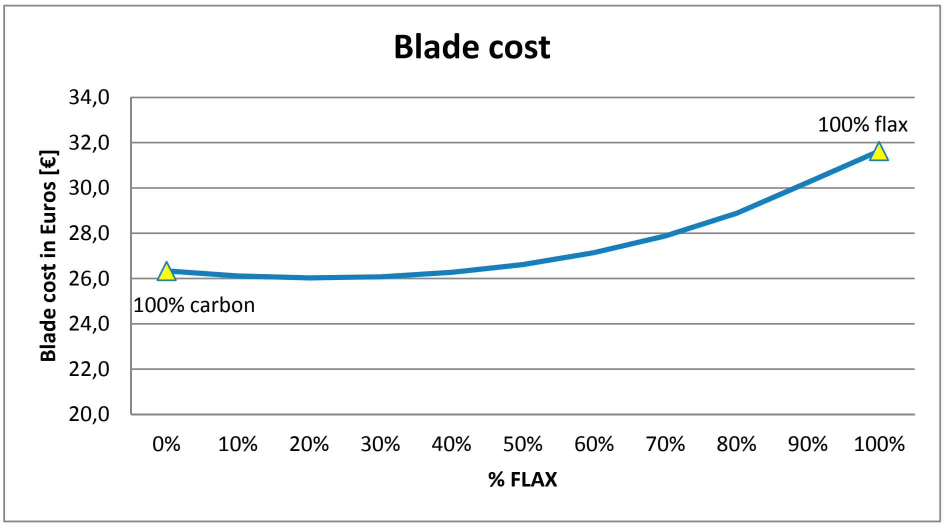

Fig. 7: Hybrid blade cost in Euros as a function of the ratio of flax applied.

In Fig. 8, the results are shown for Δ-LCA comparing a flax blade made with bio-based resin and one with conventional epoxy resin.

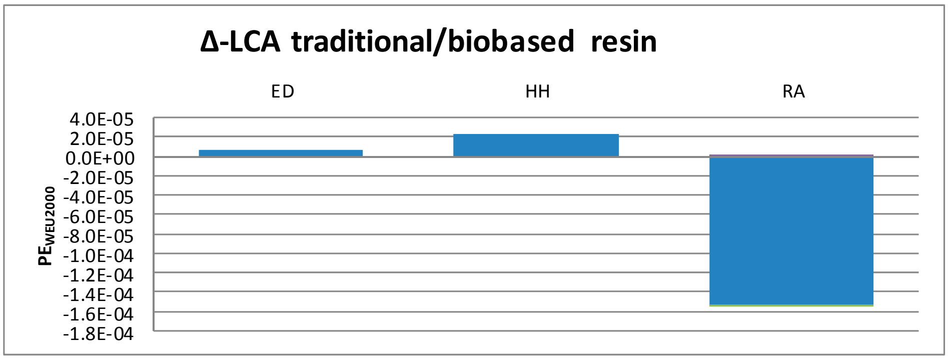

Fig. 8: Impact assessment results on both endpoint level comparing the impact of a flax blade with conventional resin and bio-resin.

4. DISCUSSION

A general view on the LCA results on the four different materials as presented in Figs. 1-3 clearly indicate that the hybrid blade has the best environmental performance. This observation is in accordance with the fact that the hybrid blade combines the low non-renewable resource depletion related with the flax fibers, the high specific stiffness of this blade type, and the low resin uptake of the carbon fibers.

On the other hand, the glass fiber blade has the worst environmental performance (see Figs. 1-3). This is because the production process for glass fibers in general is more environmentally burdensome than the one for flax fibers, and comparable burdensome to the one for carbon fibers. Additionally the glass fibers itself has poor specific stiffness, necessitating a higher mass in order to obtain the same flexural stiffness as the other alternative. The high mass of the glass fiber blade type further increases the environmental burden of the transport phase. For a detailed analysis of the carbon, flax, and hybrid 50-50 scenario, see Markussen et al. (2013).

Focusing on the Δ-LCA results (Fig. 4) it is observed that all the other materials perform better than the glass blade. Compared to the flax blade, the glass blade has higher a contribution to Resource Depletion. This is caused by the production process and the transport process (flax fibers are assumed produced in Europe, while carbon and glass fibers are produced in China).

In Fig. 4, the hybrid/glass blade comparison reflects the same issues; however in addition there is a higher contribution to Human Health damage for the glass fiber blade mainly caused by the difference in mass between the two blade types, which causes an increase in the emissions related to the transport stages. This pattern is also observed for the carbon/glass blade comparison.

The carbon/glass blade comparison reveals no large differences in terms of Resource Depletion since both of the fiber production forms require considerable amounts of energy.

The single score results on the hybrid blade covering different flax:carbon ratios indicate that there is a minimum for the single score, as presented in Fig. 6. The optimal solution is a ratio of 70% of flax fibers and 30% of carbon fibers.

As presented in Fig. 5, by increasing the amount of flax fibers leads to a decrease in the Resource Depletion; however, on the other hand, since flax fibers have a low volume fraction, the more flax fibers require more resin. Increasing the amount of resin implies that Human Health damage is increasing since Human toxicity is mainly related to the production and use of the epoxy resin.

As observed in Fig. 7, there is a minimum cost of the hybrid composites. This minimum cost solution seems to have the same flexural performance as the other alternatives, and it takes place at approx. 20% flax fibers and 80% carbon fibers. The price of flax fibers is high because there is only a small demand for this product. Carbon fibers on the other hand have over the last decade shown a remarkable decrease in price mainly caused by the high demand for this product.

As presented in Fig. 8, the application of a bio-based resin reduces the overall environmental burden of a blade. Flax blades however have the highest resin uptake among all the blade alternatives compared in the present case study.

5. CONCLUSIONS

In the study at hand, it has been demonstrated that the optimum material in terms of environmental sustainability performance, is a hybrid solution consisting of 70% flax fibers and 30% carbon fibers. This ratio is however not the cheapest hybrid alternative.

At the same time, it has been demonstrated that in terms of cost, the optimum solution is a 20% flax and 80% carbon hybrid solution.

Despite the fact that the optimum solutions in terms of environmental performance and cost are different, the data uncertainty related to the assessment does not allow for judgment of whether the two optima are different or not.

The use of a bio-based epoxy resin shows an increase in the environmental performance. This is an interesting observation, since despite being of “bio” origin these materials still have a considerable environmental burden.

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