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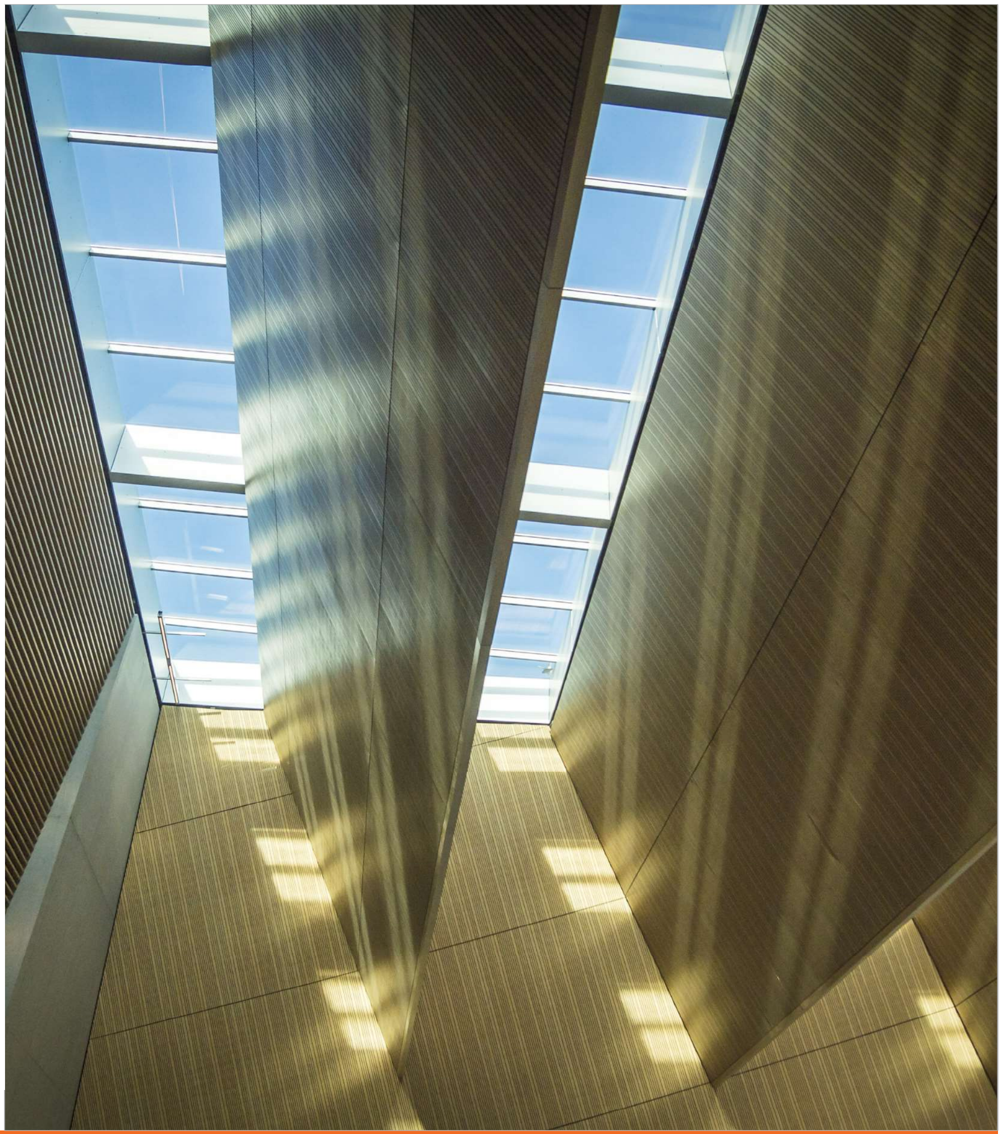

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Vol 6 – Life Cycle Assessment

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COMPARATIVE LIFE CYCLE ASSESSMENT OF THERMOPLASTIC AND THERMOSETTING CFRP IN AEROSPACE APPLICATIONS.

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Abstract: *This work quantifies and compares the environmental impact of a thermoset CFRP aircraft skin panel to that of a thermoplastic CFRP panel. This comparison is done using a cradle to gate life cycle assessment including impacts from raw material extraction, manufacturing and end of life. In addition, a hotspot analysis was performed to identify processes with the highest contribution to environmental impacts of the panels. The results show that the thermoplastic panel performed better in three endpoint damage categories including damage to human health, ecosystem and resources. The results also identify carbon fibre production, electricity usage for curing/consolidation and prepreging as the major contributors to the life cycle impacts of both panels. This provides decision makers with insights on where to focus on for future improvement actions aimed at reducing the environmental footprint of CFRP structures.*

Keywords: Life Cycle Assessment (LCA); Environmental Impact; Carbon Fibre Reinforced Polymers (CFRP); Thermoset (TS); Thermoplastic (TP).

1. INTRODUCTION

The drive for sustainable aviation has raised increasing interest in Carbon Fibre Reinforced Polymers (CFRP). This is due to their excellent specific strength and stiffness which are desirable properties in aerospace structures. According to C. Soutis, [1] weight reduction of over 20% can be achieved by replacing metals with CFRP in both primary and secondary structures. This results in a significant improvement in fuel efficiency of aircrafts and is projected to contribute up to 15% of aviation CO2 reduction targets by 2050 [2][2].

CFRP parts can be manufactured using either a thermoset or thermoplastic matrix system. So far, most CFRP aircraft structures are realised with thermosetting matrix. This is due to their low processing viscosity, low curing temperature and moderate non-recurring cost. Although these properties make thermoset (TS) CFRP suitable for small volume production, there are still challenges associated with their joining methods, low fracture toughness and end of life. Due to these limitations, interest in thermoplastic (TP) CFRP have increased significantly in recent years[3]. TP CFRP provide potentials for better recycling, alternative joining methods and better intrinsic fracture toughness. However, their high processing temperatures is a major downside. Thermoplastic CFRP are manufactured at significantly higher temperatures than thermoset CFRP. Which may lead to more energy consumption and use of special moulds to withstand high temperature conditions. The question is “is the overall environmental performance of TP CFRP better than TS CFRP, despite its limitations in manufacturing?”. This question cannot be answered without taking a life cycle perspective.

Some studies have assessed the environmental impact of CFRP used in aerospace applications. Most of these studies have focused on the impacts of thermoset CFRP in comparison to other

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materials including aluminium and steel [4][5]. Others have assessed the impact of different processing routes for thermoset CFRP [6]. However, with the advent of thermoplastic CFRP in aerospace applications, only a few studies have assessed their overall life cycle impacts and compared them to thermoset CFRP. Katsiropoulos et.al., [7] compared life cycle impact of a helicopter's canopy made with Carbon Fiber /epoxy to that from Carbon Fibre/PEEK. Although this study included impacts from raw material extraction, manufacturing and end of life of the panels, it only considered one impact category – Global Warming Potential (GWP). Also, the primary data used in this study was obtained only from literature.

The goal of this study is to benchmark the environmental impact of an aircraft skin panel made from thermoset CFRP against a thermoplastic CFRP panel. Also, to identify hotspots or high impact activities throughout the life cycle of the compared panels. This would guide future impact reduction efforts.

2. METHODOLOGY

2.1 Life Cycle Assessment Methodology

Life cycle assessment (LCA) is a standardized framework for assessing the impact of a product system on human health, ecosystem quality and natural resources. It involves the collection and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle [8]. LCA also covers a wide range of environmental issues, allowing most environmental impacts associated with a process or system to be identified instead on focusing on just one impact for instance climate change. In this study, the impacts of a thermoplastic CFRP panel was bench marked against that of a thermoset CFRP panel. This was done in accordance with ISO 14044 and 14400 and include the following steps: goal and scope definition, inventory analysis, life cycle impact assessment (LCIA) and interpretation.

2.2 Goal and Scope Definition – Functional Unit and System Boundary

Functional unit is the quantitative reference for comparison and provides the same functional performance for the systems compared. In this study, functional Unit is defined as 450X450X2mm aircraft skin panel with a fiber volume fraction Vf of 55%. Raw material and manufacturing data for the carbon fibre (CF) prepregs used in the two panels were normalized to have similar panel areal weight, panel thickness, fiber volume fraction and fiber orientation to ensure comparable strength and stiffness [9]. In this study, a cradle to gate system boundary was adopted considering three phases: raw material extraction, manufacturing and EOL. We assumed the compared panels have only a small weight variation and have similar maintenance therefore the use phase would be identical. The joining methods and assembly steps for the two panels were not considered.

2.3 Life Cycle Inventory Analysis

Inventory analysis quantifies elementary flows from all process steps in the studied product system. In this study, the energy and material flows for each processes in the raw material stage, manufacturing and end of life were quantified using data from literature, databases or direct measurements. Details are shown in subsections below.

2.3.1 Raw Material Stage

The raw materials needed to manufacture a CFRP panel is mainly the carbon fibre, polymer matrix and consumables. For this study, carbon fibre prepregs were used. For thermoset CF/Epoxy panel, Deltapreg M30Sc-150-DT was used and for the thermoplastic CF/PPS panel, Toray T300JB was used. Inventory data for the polymer matrices (Epoxy and PPS) and consumables were obtained from the ecoinvent 3.5 database [10]. However, details of the manufacturing process used to produce these consumables were obtained from Witik et.al. [11]. LCI data for carbon fibre production is not represented in ecoinvent database, so process steps for CF production was modelled in this study using process description and data obtained from Das [12] and Pillain et al. [13]. The quantity of consumables and CF-prepregs used during manufacturing were obtained by direct measurement. However, the CF/Matrix weight compositions were obtained using fiber areal weight provided in the prepreg manufacturer data sheet alongside panel size, and weight of cured laminate.

2.3.2 Manufacturing Stage

Panel manufacturing was carried out at the Delft Aerospace Structure and Materials Laboratory (DASML), TU Delft. CF/Epoxy panel was manufactured using manual collation and autoclave curing while the CF/PPS panel was fabricated using manual collation and forming in a hot press. The process steps for each panel is shown in figure 1.

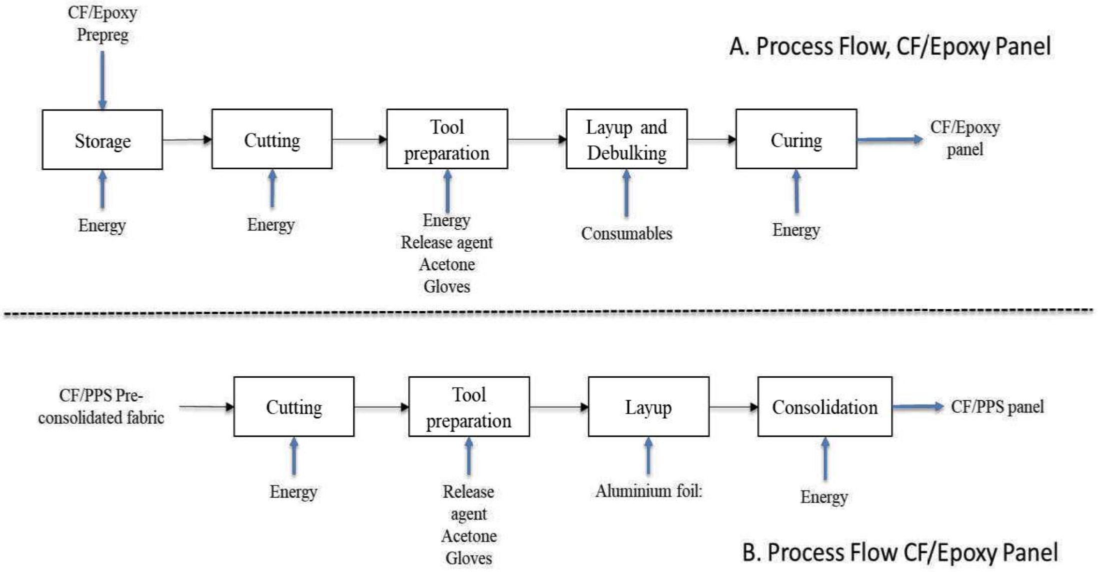

Figure 1 Process flow chart for Manufacture of CFRP Panel. product A = CF/Epoxy panel and product B is CF/PPS Panel

The prepreg/preconsolidated fabrics and consumables were cut into desired part shape and dimension using a CNC automated Gerber cutting machine. Energy use of the cutting machine during operation was measured using a power meter. The cut composite plies were manually laid up on aluminum moulds and consumables for each process were added, these were weighed and recorded prior to layup. Vacuum pump was used at interval when collating the thermoset plies to suck out excess air (debulking) and to ensure the vacuum bag was properly sealed prior to curing. The energy consumption of the vacuum pump was measured and recorded. Once layup was completed, the thermoset laminate stack was placed in the autoclave to cure while the thermoplastic stack was placed in between hot press plates to consolidate. Electrical energy consumption of the autoclave and the hot press were monitored during curing and consolidation using a power meter. Once cure and consolidation cycles were completed, the panels were cooled and weighed. After the manufacturing stage, the parts are usually moved to a joining facility for assembly. Joining methods were not considered in this study.

2.1.1 EOL Stage

Average lifespan of composite panel used in aircraft skin was assumed to be 30 years which is similar to the average operational service life of an aircraft[14] . The EOL for both panels were modelled as incineration of mixed plastics with energy recovery and data was obtained from ecoinvent 3.5 database [10].

2.2 Life Cycle Impact Assessment (LCIA)

In this stage, the elementary flows quantified from life cycle inventory are converted to environmental impacts. LCIA results in this study were calculated using two impacts assessment methods including Cumulative Energy Demand CED and ReCiPe 2016 Hierarchist method [15]. These two methods are integrated in the SimaPro 9.2 software. ReCiPe 2016 includes 18 impact categories at midpoint level and three damage end point categories.. The end point indicators cumulate these midpoint impacts into three damage categories including impact on human health in DALY, ecosystems in species.yr and resources in USD2013 [15]. Raw materials extraction and manufacturing of CFRP panel are energy intensive, hence CED was adopted to give an overview of quantity of energy utilized for each process.

3. RESULTS AND DISCUSSIONS

3.1 LCIA results

The environmental impacts of CF/Epoxy and CF/PPS panels throughout their lifecycle- (raw material production, manufacturing and end of life) is shown in figure 2.

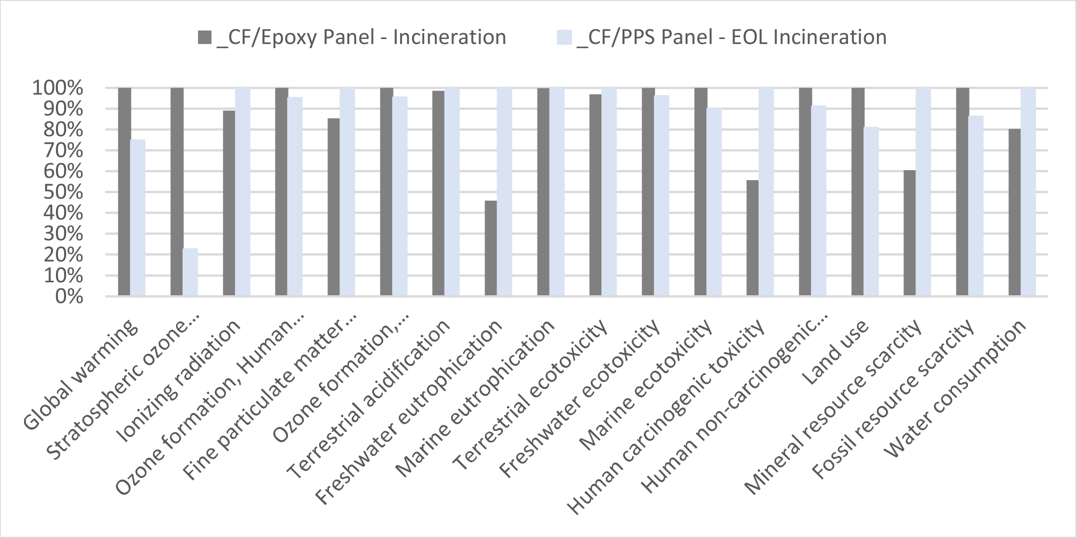

Figure 2 Environmental Impact assessment of raw material production and manufacturing of CF/Epoxy Panel and CF/PPS panels

Impacts from CF/PPS were higher in nine impacts categories including water Consumption, however it had lower impacts than CF/Epoxy in nine other impact categories including global warming. LCA studies in the aerospace industry have mostly focused on GWP impact category, presenting their results in CO_2 equivalent. However, the results in figure 2 show that although CF/PPS performed better in the global warming category, it was worse in some other impact categories. This shows the importance of taking into account a number of impacts as it provides a better representation of the environmental performance of a product system.

Figure 3 shows the end point damage categories using Recipe H method. The endpoint results show the damage to human health, ecosystem and resources and provide a more real-life perspective of the impacts. CF/PPS performed in all three damage categories including impact to human health, ecosystem and resources.

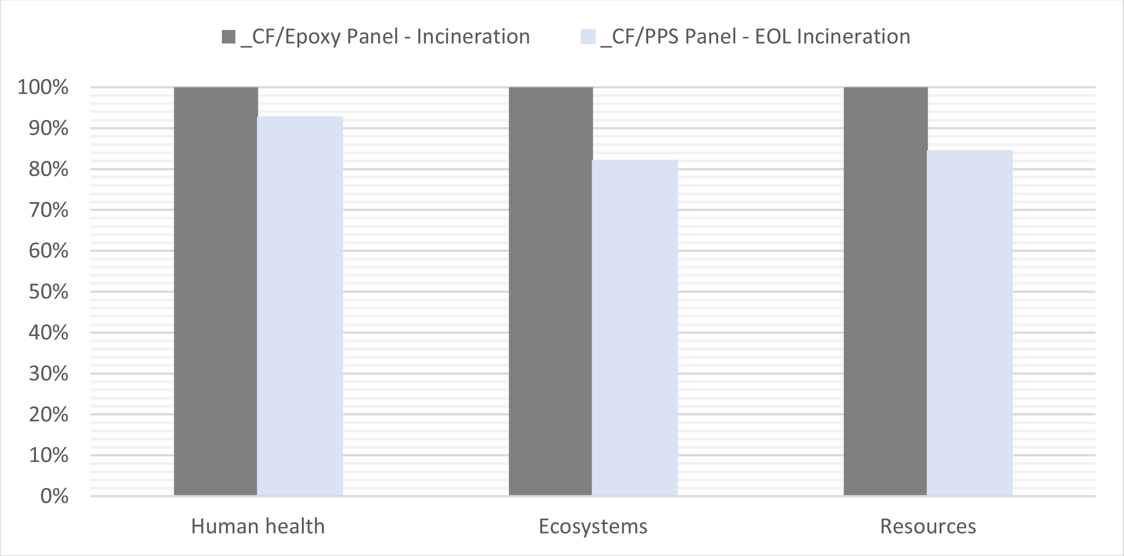

Figure 3:Cradle to gate environmental impact comparison between CF/Epoxy and CF/PPS panels.

3.2 Hotspot Analysis

Hotspot analysis is used to identify processes in a product system that contribute significantly to the environmental impact. It serves as a decision support tool that points out areas to focus on when planning to reduce environmental footprint of a product system. Cumulative Energy Demand (CED) 1.11 single score method and SimaPro 9.2 software was used in this section.

Figure 4 compares the CED of CF/Epoxy to CF/PPS throughout the lifecycle stages considered in this study. As seen, The raw material stage had the highest contribution for the two panels, followed by manufacturing. The figure also shows that at the raw material stage, the CED for CF/PPS was higher than that of CF/Epoxy. However, in the manufacturing stage, the reverse was the case. Overall, the total CED of CF/Epoxy was higher than CF/PPS by 15%.

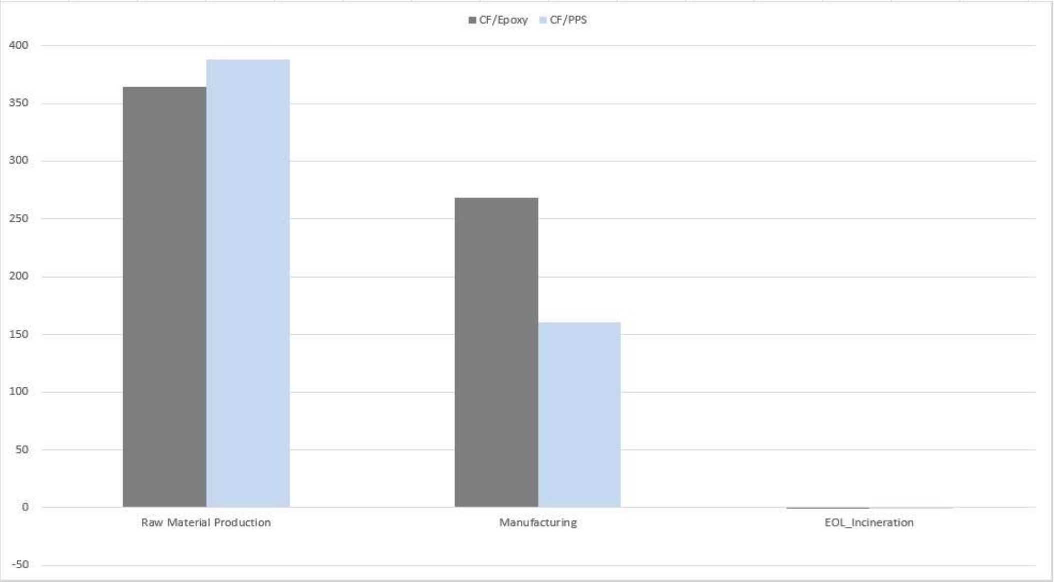

Figure 4: Life Cycle Cumulative Energy Demand of CF/PPS and CF/Epoxy

Figure 5 shows the sub-processes in CF/PPS product system that contribute to its environmental footprint for raw material production and manufacturing. Production of the CF/PPS fabric was the highest contributor to the CF/PPS product system taking up 71% of its cumulative energy demand. Consolidation of the CF/PPS panel contributed 26% of the overall CED and includes only the electricity consumed by the press during consolidation. Figure 5 further breaks down the process steps of the raw material production. This breakdown shows that production of carbon fiber contributed 57.5% to raw material production and 41% to the overall CED of CF/PPS panel.

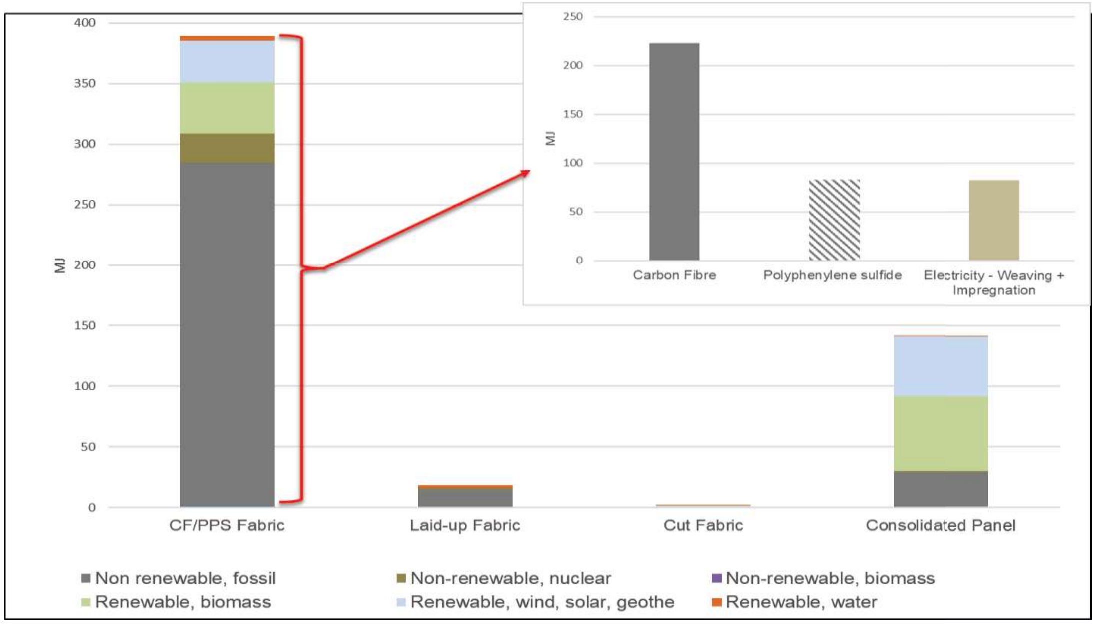

Figure 5 Process contribution for CF/PPS product system.

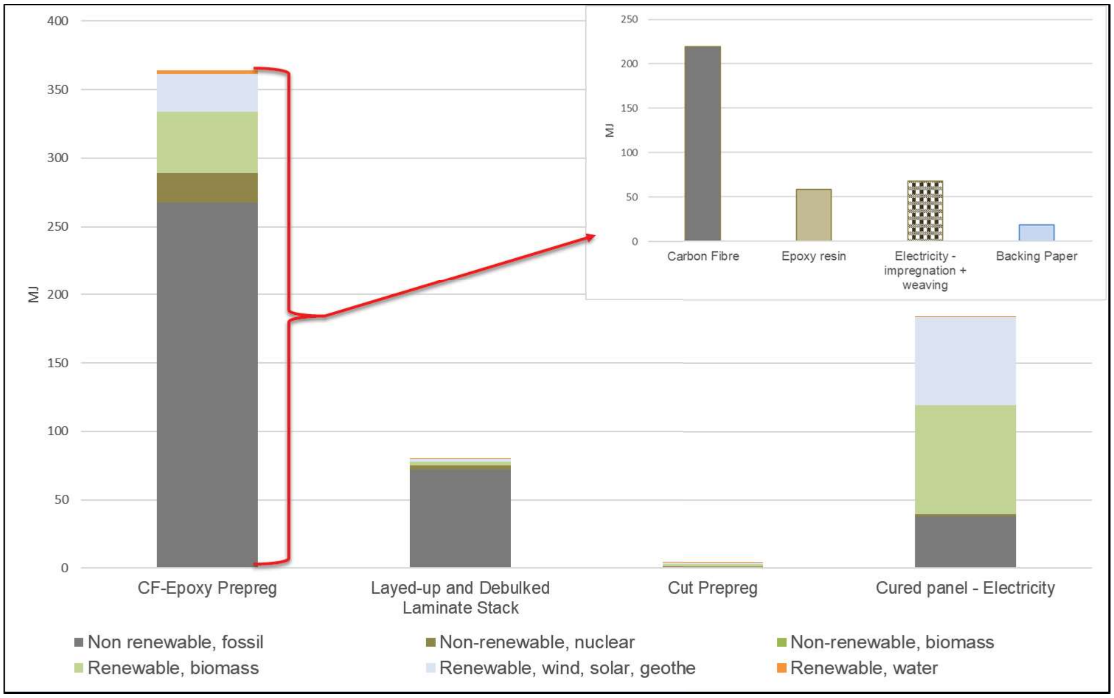

Figure 6 Process Contribution for CF/Epoxy product System.

Figure 6 on the other hand shows the process in the CF/Epoxy panel product system that contribute to its total footprint in the raw material and manufacturing stages. Again, raw material production of the CF/Epoxy prepreg had the highest contribution consuming 42% of the total cumulative energy demand. Curing of panel contributed 29% of the total energy and this includes only the electricity used by the autoclave. Layup and debulking contributed 13% of the total impacts. A breakdown of the raw material production process shows that carbon fibre production contributed 60% to raw material production and 35% of overall CED of CF/Epoxy Panel. Production of epoxy resin as well as electricity for weaving and prepreging also contributed 9% and 11% respectively to the overall CF/Epoxy panel impact.

CONCLUSION

This study compares the life cycle impact of two aircraft skin panels made from thermoset CF/Epoxy and thermoplastic CF/PPS. The results showed that at midpoint level, the TS panel performed better in nine impact categories and the TP panel was better in nine other impact categories including global warming. When impacts were aggregated at the end point levels, the thermoplastic panel performed better in all three damage categories including impact to human health, ecosystem and resources. LCA studies in the aerospace industry have mostly focused on global warming potential, presenting their results in CO2 equivalent. However, the results from this study reiterates the importance of taking into account a number of impacts as it provides a better representation of the environmental performance of a product. A hotspot analysis was also carried out to identify processes within the product systems that contributed significantly to the overall environmental impacts of the panels. Carbon fiber production contributed almost 30% to the total cumulative energy demand of the two panels considered. A strategy to reduce this impact would be recycling the CFRP parts instead of incineration or landfilling. Recycling methods for TS CFRP are still at their incipient stage, but potentials for improvement by the next

30 years (the panel lifespan considered in this study) is still there. Further studies including recycling methods as EOL pathways instead of incineration will provide more insight to their environmental benefits. Electricity consumption during curing and prepreging contributed almost 40% of cumulative energy demand for CF/Epoxy panel. Most of the electricity were sourced from the Dutch electricity grid, hence about 60% of the electricity came from non-renewable energy sources. Strategies to reduce energy consumption or to promote the use of more renewable energy sources can reduce the carbon footprint of CFRP manufacturing.

REFERENCES

[1] C. Soutis, "Use of carbon fiber-reinforced plastics in aircraft construction," *Mater. Sci. Eng. A*, vol. 412, no. 4, pp. 171–176, 2005.

[2] L. Zhu, N. Li, and P. R. N. Childs, "Light-weighting in aerospace component and system design," *Propuls. Power Res.*, vol. 7, no. 2, pp. 103–119, Jun. 2018.

[3] G. A. Vincent, "Recycling of thermoplastic composites laminates The role of processing," University of Twente, the Netherlands, 2019.

[4] S. Howe, A. J. Kolios, and F. P. Brennan, "Environmental life cycle assessment of commercial passenger jet airliners," *Transp. Res. Part D Transp. Environ.*, vol. 19, pp. 34–41, Mar. 2013.

[5] A. J. Timmis *et al.*, "Environmental impact assessment of aviation emission reduction through the implementation of composite materials," *Int. J. Life Cycle Assess.*, vol. 20, no. 2, pp. 233–243, 2015.

[6] R. A. Witik, F. Gaille, R. Teuscher, H. Ringwald, V. Michaud, and J.-A. E. Månson, "Economic and environmental assessment of alternative production methods for composite aircraft components," *J. Clean. Prod.*, vol. 29–30, pp. 91–102, Jul. 2012.

[7] C. V. Katsiropoulos, A. Loukopoulos, and S. G. Pantelakis, "Comparative environmental and cost analysis of alternative production scenarios associated with a helicopter's canopy," *Aerospace*, vol. 6, no. 1, Jan. 2019.

[8] Dansk Standard, "DS/EN ISO 14040:2008 Miljøledelse - Livscyklusvurdering - Principper og struktur," 2008.

[9] J.-A. E. MÅNSON, M. D. WAKEMAN, and N. BERNET, "Composite Processing and Manufacturing—An Overview," in *Comprehensive Composite Materials*, Elsevier, 2000, pp. 577–607.

[10] "ecoinvent 3.7.1 – ecoinvent." [Online]. Available: https://www.ecoinvent.org/database/ecoinvent-371/ecoinvent-371.html. [Accessed: 29-Jun-2021].

[11] R. A. Witik, R. Teuscher, V. Michaud, C. Ludwig, and J. A. E. Månson, "Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling," *Compos. Part A Appl. Sci. Manuf.*, vol. 49, pp. 89–99, 2013.

[12] S. Das, "Life cycle assessment of carbon fiber-reinforced polymer composites," *Int. J. Life Cycle Assess.*, vol. 16, no. 3, pp. 268–282, 2011.

[13] B. Pillain *et al.*, "Positioning supercritical solvolysis among innovative recycling and current waste management scenarios for carbon fiber reinforced plastics thanks to comparative life cycle assessment," *J. Supercrit. Fluids*, vol. 154, p. 104607, Dec. 2019.

[14] "Operating life | Airbus." [Online]. Available: https://www.airbus.com/en/products-services/commercial-aircraft/the-life-cycle-of-an-aircraft/operating-life. [Accessed: 15-Apr-2022].

[15] "LCIA: the ReCiPe model | RIVM." [Online]. Available: https://www.rivm.nl/en/life-cycle-assessment-lca/recipe. [Accessed: 01-Jul-2021].