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SUSTAINABLE BOAT DESIGN GUIDE: Materials, Manufacturing, End-of-Life and Environmental impact

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1 SUSTAINABLE MATERIALS FOR BOAT BUILDING

The fiber-reinforced plastic composite components consist of fiber reinforcements (glass, carbon, aromatic polyamide fibers) embedded in resin (epoxy, polyester, phenol-formaldehyde). While the resin gives the composite its shape, surface appearance, environmental tolerance, and overall durability, the fibrous reinforcement bears most of the structural loads, thus primarily providing macroscopic stiffness and Strength. Due to the chemical crosslinked structures, thermoset composites cannot be easily separated into their fiber and matrix components, which is the basis for the success of these versatile materials but also means they are inherently difficult to recycle. Additionally, the production of the fibers mentioned above is energy-intensive and consumes non-renewable resources. Therefore, adopting sustainable alternatives for synthetic fibers and resins in production is essential for the industry to move to a circular economy model from the current linear model.

1.1 NATURAL FIBER-REINFORCED POLYMER COMPOSITES

Natural fiber-reinforced polymer composites have gained significant attention as eco-friendly alternatives to traditional boat construction materials like glass and carbon fibers. For example Green Boats Flax 27 daysailer (El Hawary, Boccarusso, Ansell, et al 2023) or BALTIC 68 CAFÉ RACER PINK GIN VERDE, where more than 50% of the hull structure contains flax reinforcement (Baltic Yachts 2021). Incorporating more sustainable fibers reduces overall environmental impact while improving resource efficiency.

1.1.1 Plant fibers

Natural fiber composites from renewable plant-based fibers such as flax and hemp are increasingly used in boat construction. These fibers are renewable and have a lower carbon footprint than common fibers like fiberglass and carbon fiber, expecially produced from PAN. Compared to glass fiber, flax and hemp composites offer good strength-to-weight ratios, allowing lightweight boat structures. Natural fibers are available in different forms for manufacturing composite materials, as seen in Figure 1. Swiss company Bcomp™ has been developing natural fiber reinforcement technologies for several years. Its ampliTex™ and powerRibs™ solutions are successfully used in many high-performance applications, including the marine sector. To improve mechanical performance hybrid reinforcement with for example carbon fiber are introduced to market. Leaders and early adopters in the boating industry, including luxury boat specialists Baltic Yachts (Baltic Yachts, 2021), Greenboats, and Northern Light Composites, use these specific sustainable materials. Also, Chomarat and Ecotechnilin developed flax fiber products suitable for reinforcement in composite structures. (El Hawary et al. 2023)

FIGURE 1. Flax fiber reinforcements – (left to right) non-woven mat, twill weave fabric, unidirectional non-crimp hybrid with carbon fiber (Source: Centria UAS)

1.1.2 Basalt fiber

Basalt fibers are made by melting crushed basalt rock at 1400°C. The molten material is then drawn to form fiber. It has better mechanical and physical properties than glass fiber. Some of the properties of basalt fiber are fire resistance, good resistance to chemicals, vibration, and acoustic damping capacity. Because basalt remains functional at -260 °C, it is used for high-temperature and cryogenic applications. Basalt fibers are more expensive than E-glass but cheaper than carbon fiber. A manufacturer-commissioned comparison of LCA between glass and basalt fiber has shown a lower environmental impact of basalt fiber (basalatfibreworld, n.d.).

2 RECYCLED/RECYCLABLE MATERIALS IN COMPOSITES

Fiber-reinforced polymer composites utilize fibers derived from post-consumer or post-industrial waste materials, such as reclaimed carbon fiber and core materials made from recycled plastics. These composites not only divert waste from landfills but also reduce the demand for virgin materials. By incorporating recycled materials into boat construction, manufacturers can significantly reduce the environmental impact associated with the extraction and processing of raw materials. Fiber-reinforced polymer composites produced from recycled materials can exhibit comparable mechanical properties to their virgin counterparts while offering the added benefit of waste reduction.

2.1 RECYCLED PET CORE

The core materials in composites have various functions. It provides structural support to the face sheet, improves the bending resistance, reduces composite structure weight, and provides thermal and sound insulation. The choice of core material depends on the desired mechanical, cost, and environmental performance.

When environmental performance is given preference, core materials made from recycled materials provide lower impacts. The recycled PET core is made from recycled polyethylene terephthalate (PET). Repurposing PET waste contributes to a more sustainable and environmentally friendly approach to composite manufacturing. Armacell, a pioneer in PET technology, launched the structural foam core based on 100% recycled PET plastic. Other companies like Gurit sell recycled PET core material in the name of Gurit® Kerdyn™, which aligns to reduce carbon footprint and waste (Gurit, n.d.).

2.2. BIO-BASED AND RECYCLABLE RESINS

Bio-based resins and sustainable additives offer opportunities to enhance recyclability and reduce the environmental impact of boat construction materials. These alternatives to traditional petroleum-based resins provide sustainable options for boat manufacturers.

Bio-based resins, derived from renewable resources such as plant-based polymers, can replace or complement petroleum-based resins in boat construction. These resins can be designed to be easily recyclable, offering improved end-of-life solutions. In recent years, a new approach based on 'Dynamic Chemistry' has been developed for epoxy formulations to add reversible bonds into the covalently crosslinked thermoset network (Anderson et al., 2023; Lorero et al., 2022; Memon et al., 2022). A project funded under Horizon 2020 named ECOXY developed bio-based epoxy resin and studied the recyclability and reshapability of the resin (ECOxy, 2019). Bio-based resins and sustainable raw materials, such as naturally sourced reinforcements, can enhance the properties of the materials while reducing the reliance on non-renewable resources by lowering the product's environmental impact.

Biobased epoxy resins from SICOMIN are available for various manufacturing methods with varying bio-based carbon content of 28%-50%. Few other manufacturers like Entropy resins and more produce bio-based epoxy resins.

Sustainability in boat building can be achieved by shifting from conventionally used thermoset resins to recyclable thermoplastic resins that suit the manufacturing methods used in the industry. Identifying the parts that can be produced using thermoplastic composites during the designing stage reduces the amount of inert waste at the end of the product lifetime.

Composite tooling is one area where thermoplastic composites can replace thermoset resins. Traditionally plug is made by milling with the CNC shape of the product from a tooling board, which can be, e.g., polyurethane, EPS, epoxy, wood, MDF, or similar boards or blocks. The milled plug surface is perfected by applying several layers of plaster resins and surface coats. Every layer is machined by CNC and by hand. The dust created from the milling and sanding of these plug/mould building materials harms workers, making safety concerns in the production facility and compromising the production quality. CENTRIA University of Applied Sciences (Centria AMK) and the boat industry partners have been developing and testing the recyclable thermoplastic composites-based tooling.

Elium® resin from Arkema has been used to build boats with a recyclable thermoplastic polymer at the end-of-life. According to Arkema, Elium® resin is a material well adapted to the composite boats industry and their production. It is specifically adapted to the resin infusion process of large parts and has low viscosity, prolonged reactivity, and low heat of reaction. The manufactured composites at their end-of-life can be cut and crushed before the depolymerization and purification phases by which the monomer can be recovered. The monomer can then be reformulated into a new Elium® resin, therefore now a recycled resin with identical properties. The regenerated resin will reappear in construction to produce new composite parts. Mechanical recycling technologies for thermoplastic resins are well established and can be used for recycling thermoplastic composite wastes. The regrinds can create new products using thermoplastic conversion methods, such as extrusion or injection molding.

2.3 RECYCLED CARBON FIBERS

The demand for carbon fiber has continued to grow in Europe, on a year-on-year growth of 9% in 2022, as reported by AVK report on the status of the composites market. This high demand has drawbacks and is likely to increase the amount of CFRP waste dramatically over the next few years, raising questions about managing these products at the end of service life. A significant drawback of carbon fiber (CF) is that virgin carbon fiber production is an expensive and energy-intensive process, with negative environmental and health impacts from the emission of hazardous by-products (van de Werken et al., 2019). Carbon fiber production from polyacrylonitrile (PAN) is an energy-intensive process with a consumption of 50-150 kWh/kg (Wood, 2010).

One of the alternative solutions for expensive carbon fiber is to use recycled carbon fiber reclaimed from products that have reached the end of service life. Carbon fiber reclamation from end-of-life composites consumes 3-9 kWh/kg, making it much cheaper than virgin fiber (van de Werken et al. 2019). Using recycled carbon fiber is an environment-friendly approach that will reduce GHG emissions. This practice will also prevent CFRP waste from entering landfills and incineration.

Although the composite recycling industry is young and still in the early stages of development, few companies are marketing and selling recycled carbon fiber. Gen2Carbon (previously ELG Carbon) is marketing 100% recycled carbon fiber non-woven mats named G-Tex M and G-Tex TM. G-Tex TM is a comingled recycled carbon fiber/thermoplastic non-woven mat. This product is available with PP, PA, PEI, and PPS fibers, making it suitable for direct thermoplastic forming processes. Another company, Carbon Conversions, markets chopped fibers in the brand name of re-Evo® HSC and re-Evo® IMC for thermoplastic processing. Other products named re-Evo® MCF and re-Evo® MCO are non-woven mats suitable for closed/open mold infusion, pre-preg, and compression molding.

3 IMPROVING SUSTAINABILITY WITH 3D PRINTING

Manufacturing of boat structures using thermoplastic matrix composite requires novel production technologies. Material extrusion-based 3D-printing technique is used to manufacture boat components or to produce molds for conventional lamination technologies.

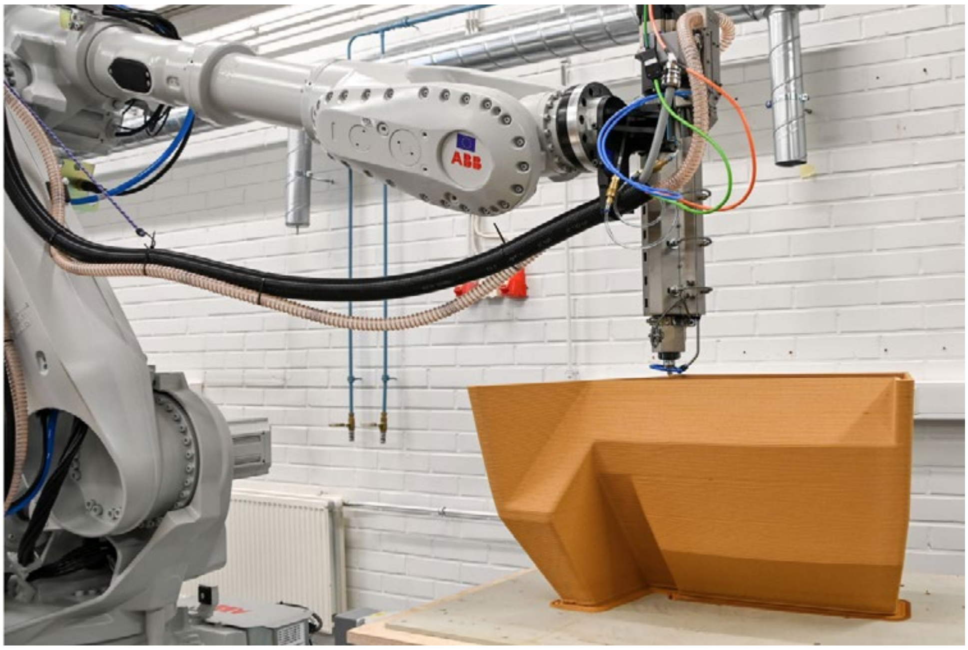


FIGURE 2. Wood plastic composite-based steering console manufacturing at CENTRIA (Source: Veneprint/Centria AMK)

In case boat components are produced, the method also provides cost efficiency since the plug/mold manufacturing step is not required when 3D-printing. From prototypes, 3D-printed boats are commercialized by different companies. CENTRIA UAS used robot-assisted 3D printing (fused granular fabrication method – FGF) to directly print a boat component that acts as a steering console, as seen in Figure 2. Customizable boat manufacturer Tanaruz is planning to scale up production of its commercial boats to 300 by 2023. Tanaruz's boats are manufactured at its Rotterdam facility using a 14-meter-long 3D printer. The boats are printed with reclaimed polypropylene containing 30 percent glass fiber to offer desirable mechanical properties, such as elongating up to five percent, alongside heat, fire, and chemical resistance.

CEAD, a Dutch OEM for large format 3D printers, has unveiled what it claims is the world's most giant robotic arm 3D printer, according to 3dprint.com. According to the report (Peels 2023), Al Seer Marine, a company based in Abu Dhabi, was the customer responsible for commissioning the 3D printer. The mega 3D printer has two robotic arms on rails and uses pellet extrusion 3D printing. It can produce complete hulls and other large structures.

FIGURE 3. Wood plastic composite-based mold before final finishing stage (left) and carbon fiber reinforced part released from the mold (right) (Source: Veneprint project/Centria AMK)

3D printing can also be utilized to manufacture a mold for conventional boat manufacturing. CENTRIA UAS, in collaboration with MMI Company Ltd., a mold manufacturer for the composite industry, developed large-scale 3D-printed molds for the boating industry. The material used to produce the mold was polypropylene filled with waste wood flour reclaimed from the plywood industry. By shifting from the conventional mold building, the company has benefited from the lowered environmental impact of their products and improved the healthy working conditions in the factory by eliminating the generation of dust from conventional milling activities. The mold seen in Figure 3 (left) can be ground and can be used to print new molds without compromising mechanical properties for two more life cycles.

4 RECYCLING AND END-OF-LIFE SOLUTIONS

Although the composite materials have a long product lifetime, the first-generation windmills and boats are nearing their end of service life. This creates a problem of identification and proper management of the composite wastes. European Boating Industries (EBI), which represents the recreational boating and nautical tourism industry in Europe, has stated that by around 2030, there will be 30000-40000 boats available for dismantling. The report further estimated that the amount of composite waste generated from a single boat averages around 0.77 tonnes. This will result in about 38000 tonnes of composite waste to be managed. (European Boating Industry 2023) Therefore, there is an urgent need to find suitable waste management methods for different types of composite wastes generated by industry. The report mentioned above also has proposed a recycling pathway for the boat waste as seen in Figure 4. This suggests recycling glass fiber-reinforced composites by Cement kiln route and finding new alternatives for recycling other composite wastes such as carbon fiber-reinforced composites to recover the valuable carbon fiber and possibly utilize depolymerized/decomposed fragments from matrix resin.

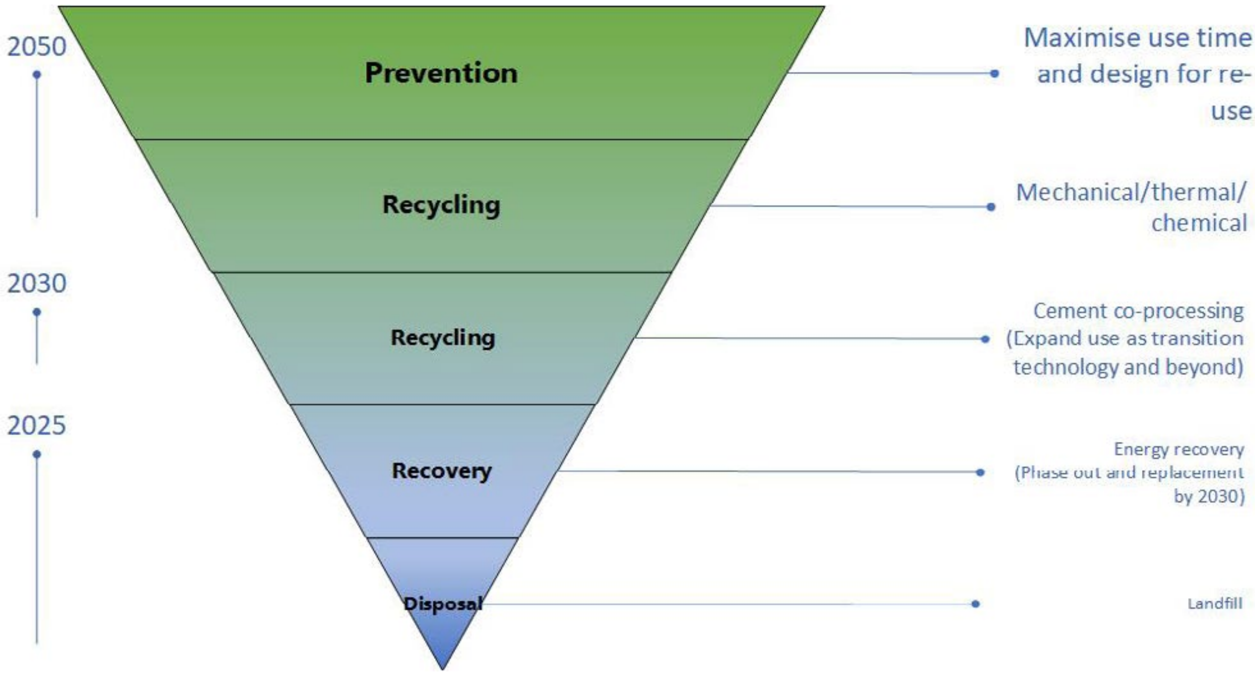


FIGURE 4. Proposed recycling pathway for boat waste management until 2030 and 2050 by European Boating Industry (EBI) (Adapted from European Boating Industry 2023)

4.1 DESIGNING FOR RECYCLABILITY

Designing boats with recyclability in mind is crucial to minimize waste and maximize the recovery of valuable materials. By considering recyclability at the design stage, manufacturers can significantly reduce the environmental impact of their boats' disposal and help promote a circular economy.

The selection of materials that are readily recyclable and compatible with existing recycling processes is critical.

- Recycling is made easier, for example, by using mono-material structures or easily separable materials.
- Designers can choose recyclable materials like thermoplastics, aluminum, or composites that can be efficiently processed at the EOL of boats.
- Designing boats to make them easy to disassemble and separate is essential for recycling efficiency. Techniques such as modular design, snap-fit connections, or standardized fasteners can make it easier to disassemble the boat.
- Sorting and recycling processes can also be aided by incorporating labeling or identification systems for different materials.

4.2 DISPOSAL AND RECYCLING STRATEGIES

Proper disposal and recycling strategies are essential to manage boats at the end of their life cycle. Recovering valuable materials, minimizing waste, and reducing environmental impact is achieved by implementing effective strategies.

Proper storage, transport, and dismantling procedures to minimize potential environmental hazards are part of the appropriate handling of end-of-life boats. Responsible recycling involves working in partnership with certified recyclers with the necessary expertise and infrastructure to deal with the recycling of boats. Complying with environmental legislation and following best practices is essential.

There are several options for the end-of-life management of boats, depending on material composition, size, and local regulations. These options include:

- refurbishment, reuse of specific boat components for other applications
- material recycling, co-processing (cement kiln route), energy recovery, etc.

Manufacturers and boat owners can choose each boat's most sustainable and efficient approach by exploring the different end-of-life management options regionally or through cross-border cooperation with relevant stakeholders. Below are the currently successfully tested recycling methods, those near commercialization and under development. Also, a schematic description of mechanical and chemical recycling methods can be found in Figure 5.

- cement co-processing
- mechanical recycling
- thermal recycling (pyrolysis)
- chemical recycling (solvolysis)

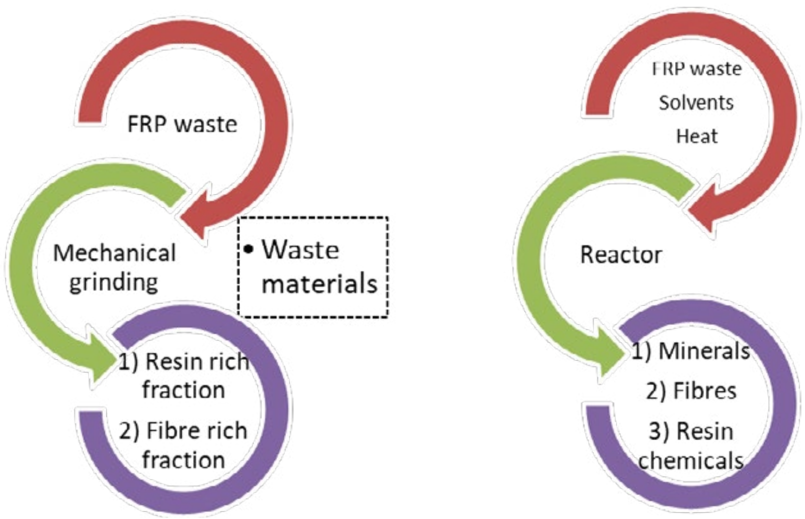


FIGURE 5. Overview of mechanical grinding (left) and chemical recycling (right) methods for composite waste

5 ENVIRONMENTAL IMPACT ASSESSMENT

Life cycle assessment (LCA) is a valuable methodology that can be used to assess the environmental impact of boats throughout their entire life cycle. LCA provides a comprehensive evaluation of a boat's environmental aspects and potential impacts, considering the extraction of raw materials, manufacturing processes, use phase, and end-of-life management. By quantifying and analyzing environmental indicators, LCA enables designers and manufacturers to make informed decisions to minimize the carbon footprint of boats.

5.1 LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

LCA methodology involves several stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. During the inventory analysis, data is collected on energy consumption, material inputs, emissions, waste generation, and other relevant factors associated with each life cycle stage. The impact assessment stage evaluates the potential environmental impacts based on indicators such as greenhouse gas emissions, resource depletion, air and water pollution, and ecosystem quality. (Hauschild, Rosenbaum & Olsen 2017)

LCA enables designers to evaluate the environmental impact of different boat designs and identify areas for progress. It helps assess the impact of design choices, materials, manufacturing processes, energy consumption, and end-of-life management strategies. LCA provides a holistic view of a boat's environmental performance by considering its entire life cycle, including upstream, core, and downstream processes.

5.2 LIFE CYCLE ASSESSMENT OF MATERIALS

An essential part of sustainable design is assessing the environmental impact of materials used in boat-building. Life Cycle Assessment (LCA) comprehensively evaluates the environmental impact of a material throughout its life, including extraction, production, use, and disposal. LCA considers energy, greenhouse gases emitted, water used, and waste produced.

LCA helps identify potential environmental hotspots and quantify the overall environmental footprint when considering sustainable materials for boat-building. This tool allows designers and manufacturers to make informed decisions, comparing materials based on environmental performance and choosing lower-impact options.

To understand the benefits and challenges of using sustainable materials, it is essential to compare them with traditional materials. Traditional composite boat-building materials like fiberglass and carbon fiber often have significant environmental drawbacks, including high energy consumption and GHG emissions when manufactured.

Through comparative studies, sustainable materials can be evaluated based on various parameters such as resource consumption, greenhouse gas emissions, toxicity, and end-of-life considerations. This analysis enables more informed decision-making by identifying the strengths and weaknesses of sustainable materials compared to traditional options. A comparison between natural and conventional fibers can be seen in Figure 6.

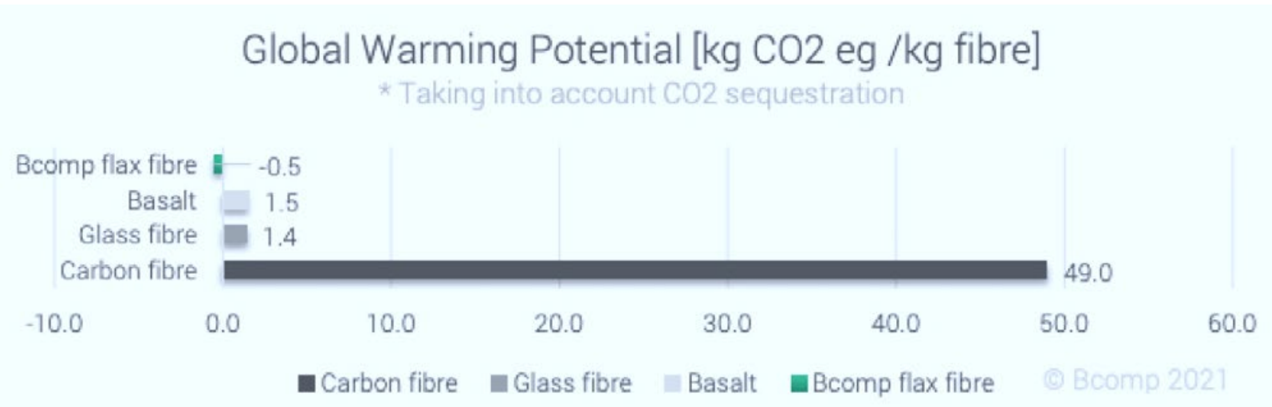


FIGURE 6. Comparison of bio-based fibers with conventional fibers in terms of global warming potential indicator (Adapted from 11TH HOUR RACING TEAM 2021)

By exploring fiber-reinforced composites as eco-friendly alternatives, including natural fiber composites and recycled fiber composites, and incorporating life cycle assessment considerations, the boating industry can make significant progress toward sustainable boat construction. By choosing materials with lower environmental impacts and understanding the life cycle implications, boat designers and manufacturers can contribute to the industry's overall sustainability while maintaining high-performance standards.

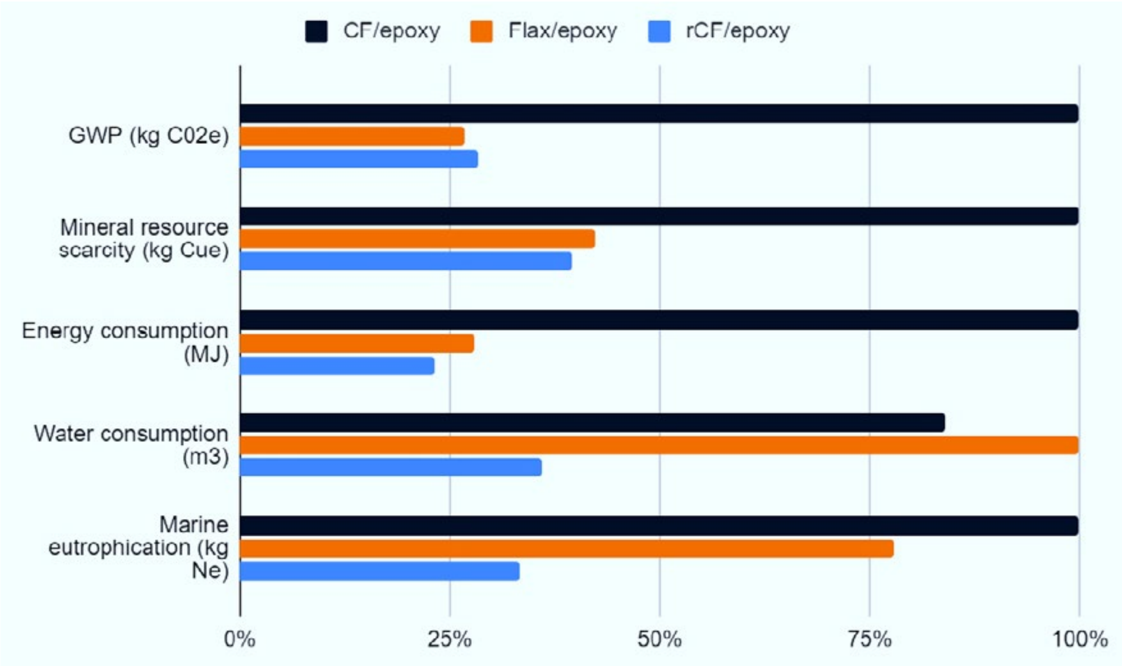


FIGURE 7. Comparing three different composites made from flax, carbon fiber, and recycled carbon fiber (10 m2) (Adapted from 11TH HOUR RACING TEAM 2021)

In the above image (Figure 7), a comparison of a 10 m^2 epoxy-based composite structure made from carbon fiber, recycled carbon fiber, and flax fiber can be seen. The higher environmental impacts of virgin carbon fiber compared to recycled and bio-based fiber are due to the high energy needed to transform the polyacrylonitrile (PAN) into carbon fiber. The higher environmental impact for flax is water consumption, which is related to flax cultivation. Generally, another indicator showing higher impact in the case of bio-based plant fibers is land use due to the land occupation for cultivation of the plant fibers. Another impact category that shows a higher impact for bio-based fibers is Eutrophication due to the fertilizer use during the cultivation. However, the overall environmental impact of bio-based composite materials is much lower than that of carbon fiber composite.

The Environmental Product Declarations (EPD) are voluntary documents for a company or organization to present transparent, consistent, and verifiable information about the environmental performance of their products (goods or services). The product category rule (PCR) complements the general program instructions (GPI) and the normative standards by providing specific rules, requirements, and guidelines for developing an EPD for one or more specific product categories.

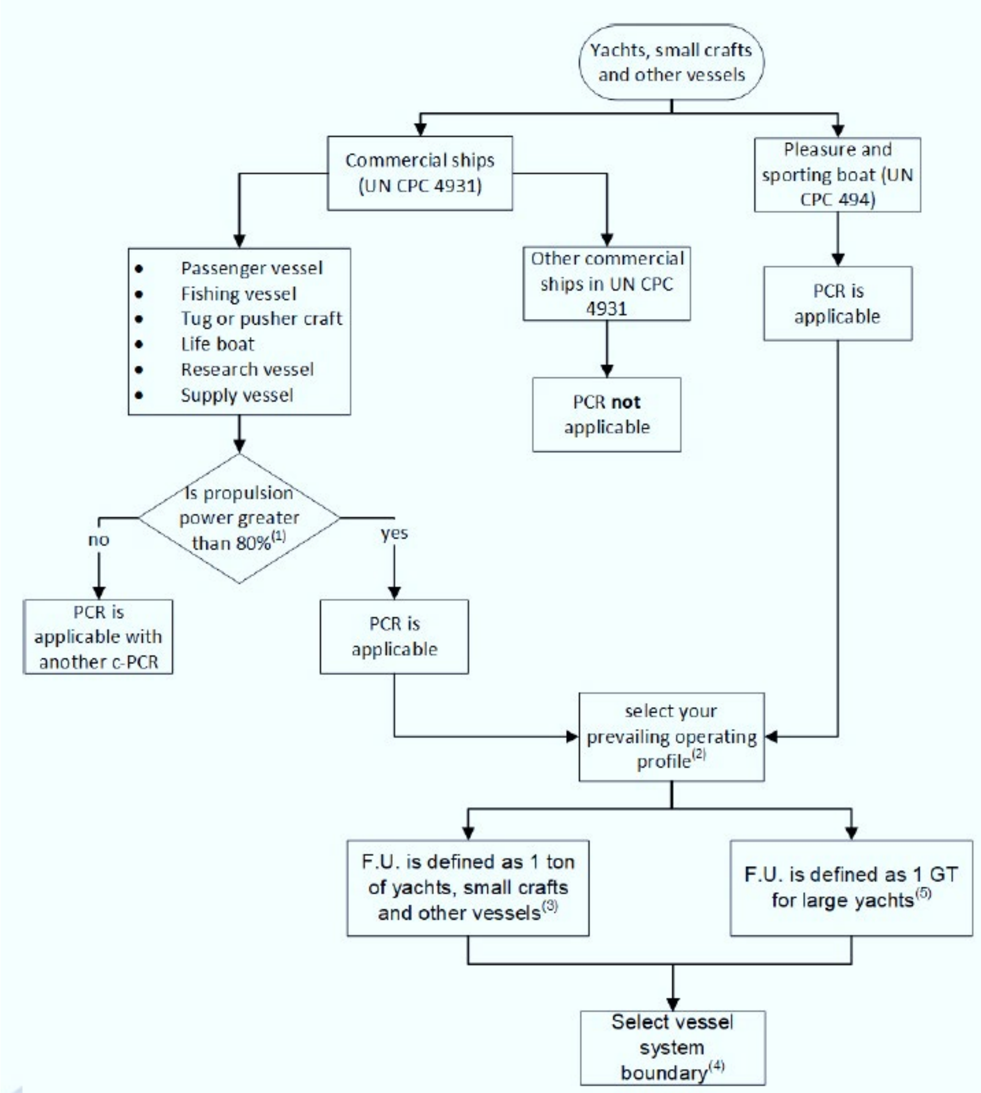
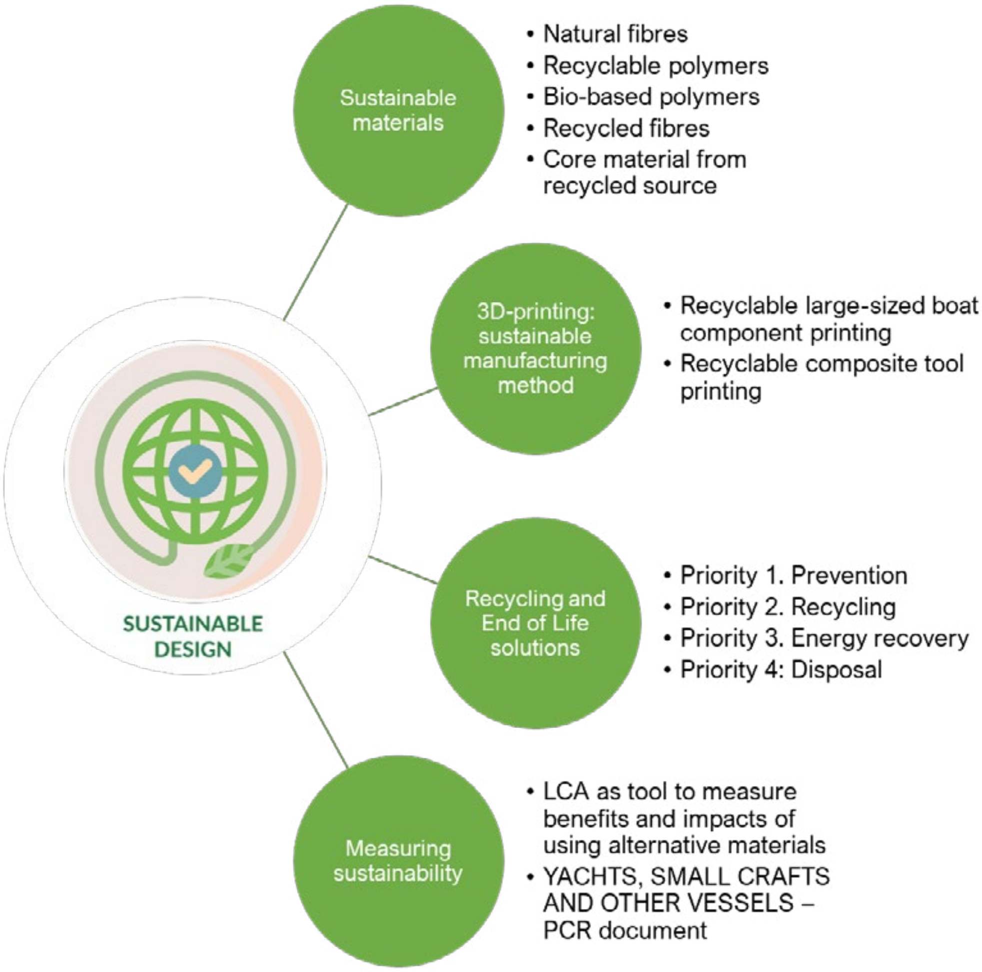


FIGURE 8. Overview of how this PCR document can be used directly, or together with a c-PCR, to develop an EPD (Adapted from 11TH HOUR RACING TEAM 2021).

YACHTS, SMALL CRAFTS, AND OTHER VESSELS – The PCR document serves as the main PCR for yachts, small crafts, and other vessels and as a basis for the development of complementary PCRs (c-PCRs) for more specific product categories of product systems about the naval sector. An overview of how this PCR document can be used directly or together with a c-PCR to develop an EPD can be seen in Figure 8. An EPD that uses a functional unit for components of vessels needs a c-PCR. This PCR is currently under modification and will be published in Autumn 2023.

6 CONCLUSIONS

The boat-building industry can significantly reduce waste, conserve resources, and minimize the environmental impact of boat disposal by considering recyclability at the design stage, exploring the use of bio-based resins and sustainable additives, and implementing appropriate disposal and recycling strategies. These strategies contribute to developing a circular boat-building economy, where boats are designed, manufactured, used, and ultimately recycled in an environmentally responsible way.



The industry can make significant progress towards sustainable boat-building by exploring fiber-reinforced composites as environment-friendly alternatives, including natural and recycled fiber composites, and by incorporating life cycle assessment considerations. Boat designers and manufacturers can contribute to the industry's overall sustainability by choosing materials with a lower environmental impact and understanding the life cycle impacts while maintaining high-performance standards.

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SUSTAINABLE BOAT DESIGN GUIDE:

Materials, Manufacturing, End-of-Life and Environmental impact

Over the past few years, there has been a growing global awareness of the importance of sustainable practices in various industries, including the boat-building sector. Boat design directly affects the environmental impact, energy efficiency, and overall ecological footprint of boats. It, therefore, plays a crucial role in ensuring long-term sustainability.

Traditionally, factors such as performance, speed, and aesthetics have been the primary focus of boat design. However, there is an urgent need to move towards sustainable boat design practices due to growing concerns about climate change, pollution, and the deple-tion of natural resources. Sustainable boat design aims to preserve marine ecosystems and reduce carbon emissions by minimizing negative environmental impacts while maximizing the efficiency and durability of boats.

Sustainable boat design covers several aspects, such as the materials used in the construc-tion, the propulsion systems, the waste management, the energy generation and consump-tion, and the entire life cycle of the boat. Boat manufacturers and designers can minimize the use of non-renewable resources, reduce emissions, and improve the overall environ-mental performance of boats by adopting sustainable design principles.

This guide provides a comprehensive overview of sustainable boat design, specifically fo-cusing on materials, manufacturing methods, end-of-life, and environmental impact. The guide examines various aspects of sustainable boat design, including sustainable sources of raw materials for fiber-reinforced composites, emerging technologies, and best practices to create greener, more resource-efficient boats. It seeks to inspire boat designers, manufac-turers, policymakers, and other stakeholders to embrace sustainable boat design to ensure the boat industry's long-term viability while preserving the health of our oceans and water-ways.

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