

GRADIENT-BASED OPTIMIZATION OF SUSTAINABLE ROTOR BLADE DESIGNS FOR LARGE-SCALE WIND TURBINES

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Abstract

The recyclability of wind turbine rotor blades has become a key challenge for the sustainable expansion of wind energy. Current blades are predominantly manufactured from fibre-reinforced polymer composites, which are difficult to recycle at the end of their service life. To address this issue, this study investigates sustainable rotor blade design concepts that combine recyclable construction strategies with alternative bio-based materials. The objective is to evaluate the trade-off between improved sustainability and structural performance in large-scale wind turbine blades. The IEA 15 MW reference blade, featuring a conventional glass-fibre reinforced composite shell and a carbon-fibre reinforced main spar cap, serves as the baseline design. Building on this reference, multiple rotor blade concepts were developed and evaluated through a gradient-based, multi-stage optimization workflow.

First, preliminary aerodynamic and structural optimisation was conducted using the Wind-Plant Integrated System Design and Engineering Model (WISDEM). Subsequently, a higher-fidelity structural optimisation was performed with the gradient-based optimisation framework lightworks in combination with the beam-based solver PreDoCS. The investigated concepts include material substitutions in the blade shell and core using laminated veneer lumber (LVL), natural fibre composites, recyclable foam cores, and balsa wood cores. The reference blade design consists of glass-fibre reinforced composite shell and carbon-fibre reinforced main spar cap. The concepts were evaluated with respect to blade mass, levelised cost of energy (LCoE), and environmental impact expressed as Global Warming Potential (GWP). The results indicate that the use of sustainable materials can significantly reduce the environmental footprint of rotor blades while maintaining acceptable structural performance. In particular, concepts based on birch LVL combined with a recycled foam core and flax-fibre composites with a balsa wood core provide the most balanced solutions in terms of mass, cost, and emissions. Although these alternatives require moderate increases in structural mass

compared with conventional designs, they offer substantial benefits for material circularity and lifecycle sustainability.

By comprehensively evaluating the environmental impact, cost, and structural efficiency, the results provide guidance for industry in identifying acceptable trade-offs and practical steps toward more sustainable wind energy systems.