Recycling Wind Turbine Blades: A DSC Perspective

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1. Abstract

End-of-life wind turbine blades represent a growing technical and logistical challenge due to their complex composite structure and limited processing options. Oxidative liquefaction is a chemical recycling route, enabling high-quality fiber recovery and the generation of valuable secondary products. To support industrial implementation, improved understanding of reaction behavior and overall performance is essential. In this work, differential scanning calorimetry (DSC) is used to study the oxidative liquefaction of decommissioned wind turbine blades under liquid-phase conditions. The study provides practical insight into the main reaction stages and the autocatalytic nature of the epoxy matrix decomposition, supporting reaction control and optimization. A life cycle assessment (LCA) evaluates the laboratory-scale route and its potential for scale-up.

2. Introduction

The expansion of wind energy capacity has created a growing end-of-life (EoL) challenge associated with wind turbine blades (WTBs). Modern blades are manufactured predominantly from glass fiber reinforced polymer composites based on thermoset epoxy resins, providing stiffness, fatigue resistance, and low weight required for turbine operation. However, these materials are difficult to recycle once decommissioned [1,2]. With first-generation wind farms approaching retirement, millions of tons of composite blade waste are expected globally within the coming decades, increasing pressure on waste management infrastructure and sustainable recycling strategies [3–5].

Unlike metallic materials, thermoset composites cannot easily be remelted after curing. In addition, WTBs represent a particularly challenging waste stream due to their large dimensions, high fiber content, and heterogeneous multilayer structure consisting of laminates, adhesives, coatings, and sandwich core materials [2,5]. As a result, landfilling remains one of the dominant disposal routes despite increasing environmental restrictions.

Current recycling technologies for WTBs can generally be divided into mechanical and chemical recycling routes. Mechanical recycling is the most industrially established approach and typically involves shredding and milling of blades into secondary filler materials for cement co-processing or construction applications [6–8]. Although this route enables large-scale waste reduction at relatively low cost, severe fiber shortening and mechanical damage limit the recovered material to low-value applications.

Chemical recycling approaches aim to selectively decompose the thermoset matrix while preserving fiber quality and recovering secondary chemical products. Among these methods, oxidative liquefaction has emerged as a promising alternative for composite waste recycling [9–13]. The process operates under hydrothermal oxidative conditions, commonly using hydrogen peroxide systems to promote decomposition of highly crosslinked epoxy networks. Compared to conventional thermal recycling methods such as pyrolysis, oxidative liquefaction can operate at substantially lower temperatures while improving preservation of reinforcing fibers and enabling recovery of oxygenated chemical products [10–13].

From an industrial perspective, oxidative liquefaction offers potential energy and environmental advantages. Partially exothermic oxidation reactions may reduce external energy demand compared to conventional thermochemical recycling routes [14–16], while recent life cycle assessment (LCA) studies indicate favorable environmental performance relative to other WTB recycling technologies [12,13]. However, industrial implementation remains limited by insufficient understanding of process kinetics and scale-up behavior.

Reliable kinetic data are essential for reactor design and process optimization. However, oxidative liquefaction kinetics are difficult to investigate because the reactions occur in sealed liquid-phase systems under elevated pressure and temperature conditions [17–20]. Differential scanning calorimetry (DSC) using sealed high-pressure crucibles enables monitoring of these processes under simulated hydrothermal conditions, yet kinetic studies on oxidative liquefaction remain limited.

Therefore, this work investigates the oxidative liquefaction kinetics of EoL WTBs using DSC equipped with sealed high-pressure crucibles to simulate hydrothermal oxidative conditions. Kinetic parameters were evaluated through combined isoconversional and reaction-model-based analyses to improve understanding of the thermal conversion behavior and reaction mechanisms governing oxidative liquefaction. The resulting kinetic framework provides a quantitative basis for the design, optimization, and scale-up of oxidative liquefaction processes for EoL composite materials. In addition, a preliminary LCA was conducted to evaluate the environmental and energy demands of oxidative liquefaction and to identify critical process bottlenecks relevant for industrial implementation and scale-up.

3. Methods and Procedures

3.1. *Materials*

EoL WTBs composite waste was supplied by ANMET Sp. z o.o. (Poland).

3.2. *Experimental Procedure (Oxidative Liquefaction with DSC)*

Oxidative liquefaction experiments were performed with a NETZSCH DSC 214 Polyma equipped with high-pressure steel crucibles. This setup enabled evaluation of the thermal behavior of the system under realistic process conditions by monitoring heat flow and enthalpy changes in the presence of reactive liquid media (H_2O_2). The DSC measurement parameters are listed in Table 1. The shredded EoL WTB samples were mixed with 12 wt.% H_2O_2 solution at a 1:20 solid-to-liquid ratio (5 wt%).

Table 1: DSC Parameters. (*) Control sample to evaluate H_2O_2 decomposition behavior.

Parameter / Setup	**Description**
Sample Mass	75.12 ± 0.09 mg
Crucible	1:20 (5 wt%)
Temperature Program	Dynamic ramp from 20 °C to investigated temperature followed by isothermal hold of 3 h
Heating Rate	5 K/min
Investigated Temperatures	(190*), 235, 250, 265 °C

3.3. Kinetic Modeling and Data Analysis

Kinetic analysis was performed from DSC heat-flow profiles using NETZSCH's Kinetics Neo software. The oxidative decomposition process was monitored through the heat evolved during the reaction, and conversion (α) was calculated from the normalized cumulative heat release obtained from the DSC signal. Raw experimental profiles were analyzed without smoothing using linear baseline correction prior to kinetic analysis. The H_2O_2 decomposition regime was evaluated separately, while only the WTB oxidation regime was used for kinetic fitting.

Reaction rates were analyzed using combined isoconversional (Friedman) and model-based kinetic approaches based on standard Arrhenius formalism. Apparent activation energies were determined using the differential Friedman method without prior assumption of a reaction model, while master-plot analysis was applied to identify the governing reaction mechanism.

Based on the obtained results, oxidative liquefaction of the WTB composite was described using a two-step consecutive autocatalytic reaction model. Kinetic parameters were optimized simultaneously against the experimental conversion profiles obtained at 235, 250, and 265 °C by minimizing the deviation between calculated and experimental results. Model accuracy was evaluated using the coefficient of determination (R^2).

3.4. Life Cycle Assessment (LCA) Methodology

A preliminary LCA was performed to evaluate the environmental performance of laboratory-scale oxidative liquefaction of EoL WTBs. The assessment was based on experimental process data reported by [12] and considered the treatment of 1 kg of WTB composite as the functional unit. Three oxidative liquefaction operating conditions between 250 and 350 °C were evaluated and compared with conventional landfilling. The system boundaries included feed preparation, oxidative liquefaction, product separation, and recovery of recycled glass fibers and secondary chemicals. Climate change impact and fossil resource demand were selected as the primary indicators for engineering evaluation of the process.

4. Results and Discussions

4.1. Process-Kinetic Evaluation of Oxidative Liquefaction

The DSC measurements confirmed that oxidative liquefaction of EoL WTB composites proceeds effectively under moderate hydrothermal conditions between 235 and 265 °C. As shown in Figure *1*, increasing process temperature significantly accelerated the decomposition kinetics, shifting the main oxidation stage toward shorter residence times while increasing the maximum conversion rate. Two distinct reaction stages were identified, corresponding to initial H_2O_2 decomposition followed by rapid oxidation of the epoxy matrix. The relatively moderate operating temperatures compared to conventional thermochemical recycling processes such as pyrolysis demonstrate the potential of oxidative liquefaction as a lower-temperature alternative for composite waste treatment.

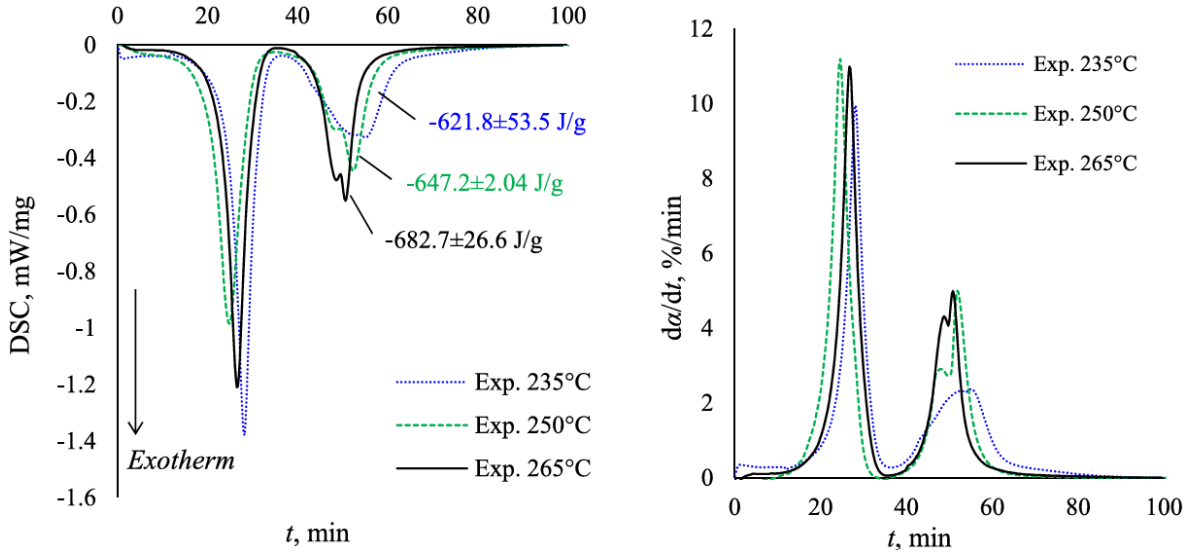

Figure 1: Experimental DSC heat-flow curves (left) and calculated conversion profiles (right) for oxidative liquefaction of WTBs at the investigated temperatures.

The process also exhibited strong exothermic behavior, with total heat release ranging from approximately −620 to −683 J/g. From an industrial perspective, this behavior is particularly

important because part of the thermal demand of the process may be internally sustained once oxidation is initiated. This creates opportunities for reduced external energy input, improved thermal efficiency, and more favorable process economics compared to conventional high-temperature recycling routes. In addition, the hydrothermal oxidative environment enabled selective degradation of the polymer matrix while supporting preservation of the inorganic fiber fraction, which is essential for higher-value material recovery.

The most relevant kinetic and process characteristics identified during oxidative liquefaction are summarized in Table 2.

Table 2: Key kinetic & process parameters relevant for oxidative liquefaction process evaluation.

Parameter	**Value / Range**	**Industrial Relevance**
Operating Temperature	235–265 °C	Lower than conventional pyrolysis
Total Heat Release/	−620 to −683 J/g	Partial self-heating potential
Apparent Activation Energy	~50–60 kJ/mol	Moderate thermal demand
Reaction Mechanism	2-step autocatalytic	Important for reactor control
Model Fit Quality	$R^2 = 0.996$	Suitable for process simulation

The conversion-rate profiles shown in Figure 2 indicate rapid acceleration of the epoxy decomposition stage once critical reaction conditions are reached. This autocatalytic behavior suggests that reaction intermediates generated during oxidation further promote decomposition, leading to accelerated conversion at elevated temperatures. For industrial reactor operation, this phenomenon is highly relevant because it directly influences heat release, residence time distribution, process stability, and temperature-control requirements during scale-up.

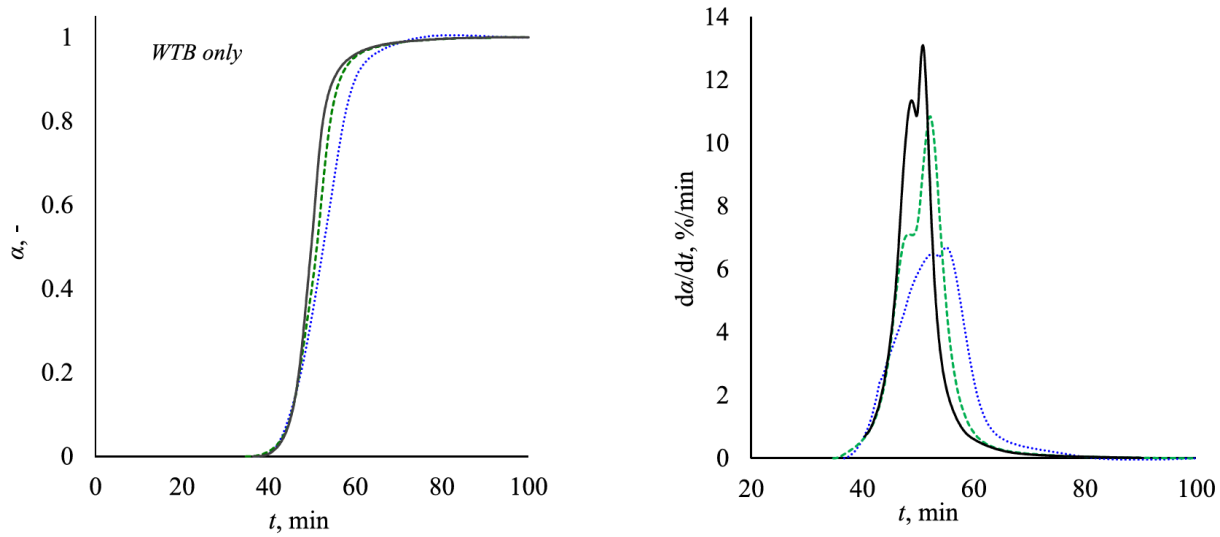

Figure 2: Conversion (left) and conversion-rate profiles (right) calculated for all investigated temperatures from the total DSC signal and the separated WTB decomposition signal.

Kinetic analysis demonstrated that the oxidative liquefaction process can be described reliably using a two-step consecutive autocatalytic reaction model. The developed model reproduced the

experimental conversion profiles with good agreement ($R^2 = 0.996$), confirming that the process behavior can be quantitatively predicted under the investigated operating conditions. Apparent activation energies in the range of approximately 50–60 kJ/mol further indicate that effective conversion can be achieved without the extreme thermal demand associated with conventional thermal recycling technologies.

Overall, the obtained kinetic and thermal data provide a practical basis for future reactor design and industrial scale-up of oxidative liquefaction for composite waste recycling.

4.2. Sustainability Assessment of Oxidative Liquefaction Processes

The LCA results highlighted the potential of oxidative liquefaction as a lower-temperature and resource-efficient recycling route for EoL WTB composites with simultaneous recovery of reusable material streams.

Figure 3 compares the environmental performance of oxidative liquefaction under different operating conditions. The 250 °C temperature process showed the lowest overall environmental burden due to reduced thermal demand and lower hydrogen peroxide consumption. Increasing process severity from 250 to 350 °C increased both climate-change impact and fossil resource demand because of higher oxidizer and energy consumption. Nevertheless, oxidative liquefaction enables recovery of reusable glass fibers and secondary chemical products under substantially milder conditions than conventional thermochemical recycling routes.

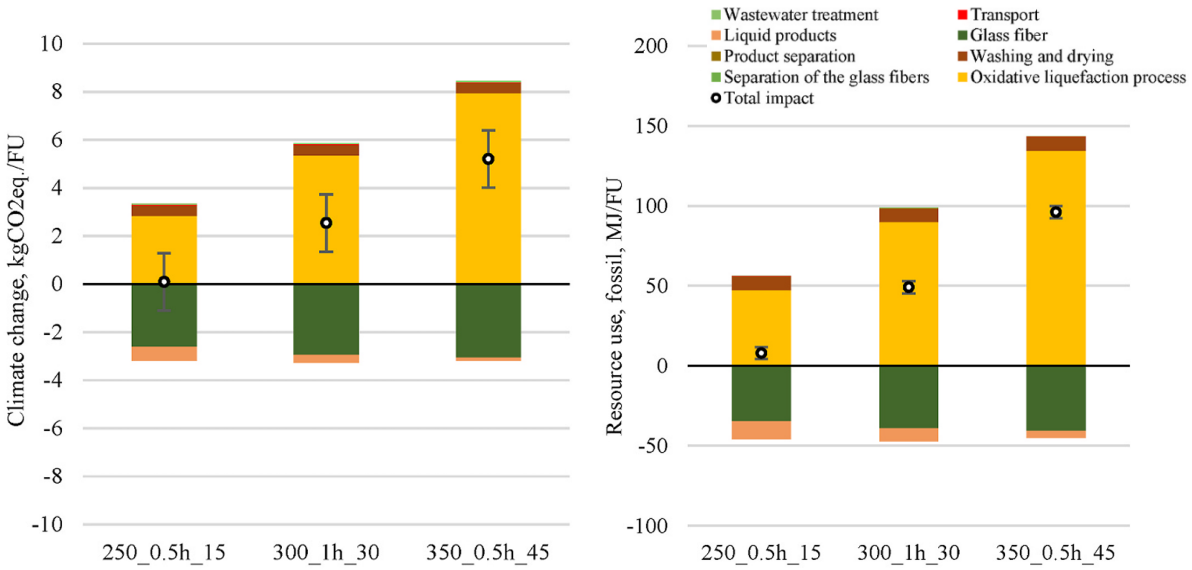

Figure 3: Environmental and energy performance comparison of oxidative liquefaction operating conditions.

Recovered glass fibers and secondary oxidation products contributed positively to the environmental balance through avoided virgin material production. From an industrial perspective, the ability to recover relatively clean glass fibers under moderate hydrothermal conditions

represents an advantage compared to mechanical recycling or high-temperature pyrolysis, where recovered fibers often experience severe quality degradation.

An example of the hot-spot analysis presented in Figure 4 identified hydrogen peroxide consumption as the dominant contributor to overall environmental impact across the investigated scenarios. In contrast, thermal energy demand and auxiliary separation processes showed substantially lower contributions. This result is particularly important for future industrial implementation because it identifies oxidizer optimization, recovery, or substitution as the primary pathway for improving process sustainability and economics.

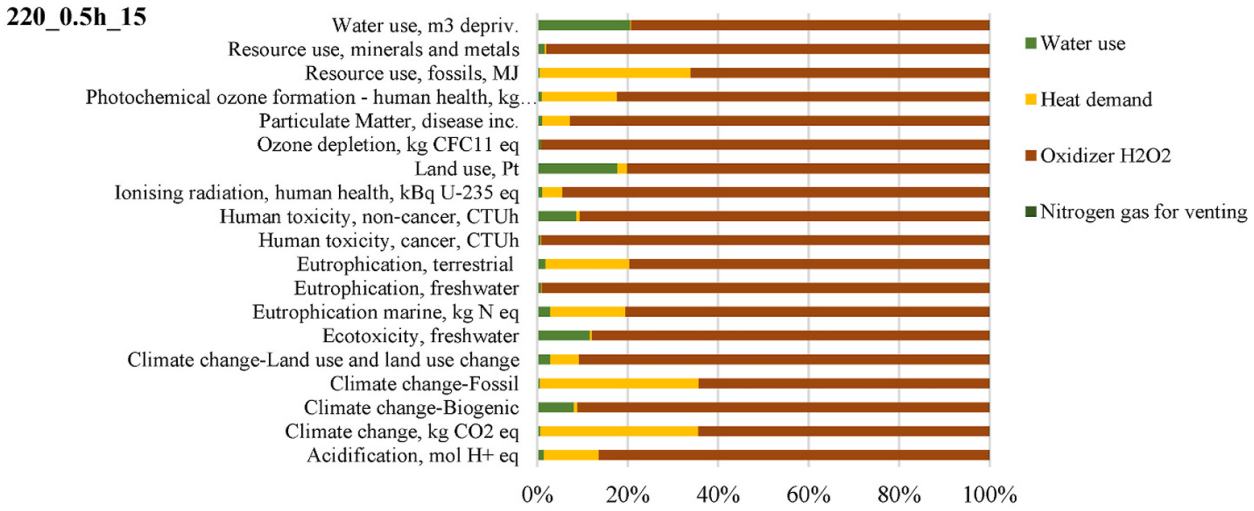

Figure 4: Simplified hot-spot analysis of the oxidative liquefaction process showing the dominant contribution of hydrogen peroxide consumption (Example shown for 220 ºC, processing time of 0.5 h, and a 15 wt% of hydrogen peroxide content in process liquid).

5. Conclusions and Future Work

Oxidative liquefaction of EoL WTB composites was successfully evaluated under hydrothermal oxidative conditions using DSC with high-pressure steel crucibles. Effective epoxy matrix decomposition was achieved at moderate operating temperatures between 235 and 265 °C together with strong exothermic reaction behavior, indicating potential for reduced external energy demand compared to conventional thermochemical recycling methods.

Kinetic analysis showed that the oxidative liquefaction process can be reliably described using a two-step consecutive autocatalytic reaction model with excellent agreement to experimental data ($R^2 = 0.996$). The obtained kinetic parameters provide a quantitative basis for future reactor design, residence-time optimization, thermal management, and process scale-up.

The LCA results further confirmed the potential of oxidative liquefaction as a lower-temperature and resource-efficient recycling route capable of recovering reusable glass fibers and secondary chemical products. Hydrogen peroxide consumption was identified as the dominant contributor to

overall environmental impact, highlighting oxidizer optimization as the primary target for future process improvement.

Overall, the combination of moderate operating temperatures, favorable thermal behavior, predictable reaction kinetics, and recoverable material streams demonstrates strong potential for industrial implementation of oxidative liquefaction as an energy-efficient recycling route for EoL WTB composites.

Future work will focus on continuous reactor operation, heat-integration strategies, and oxidizer recovery approaches to improve process efficiency, reduce environmental burden, and support industrial-scale implementation.

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