

# Microwave-assisted recycling of wind blade waste for glass fibers recovery and resin valorisation

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## Introduction

Wind turbines play a key role in the transition towards a renewable-rich energy mix to reach global sustainability and carbon-neutrality targets. Wind energy is expected to triple its installed capacity and meet 17% of global electricity demand by 2040. On average, 70 GW will be installed globally each year in the period 2018 – 2028. Given the average lifespan of the turbines (nearly 25 years) and current repowering activities that promote the replacement of wind farms before reaching their expected end-of-life to increase the installed capacity, the forecasted blade waste generation reaches about 25,000 tonnes per year by 2025 and up to 52,000 t/y by 2030, just at European level. Wind turbines manufacturing consumes a series of materials that can make recycling difficult or more expensive at the end of their lifespan. Specifically, 90% of wind turbine blades are made of composite materials (glass fibre reinforced plastics, G-FRP) and 10% of other materials such as wood, foams and metals. Currently, the options for managing such G-FRP are reduced to three: landfilling, incineration and recycling. Although landfilling has been widely employed so far, the Europe-wide ban on landfilling for such G-FRP by 2025 increases the pressure on the need to develop solutions for the recycling of these materials in a sustainable way. Given the large energy consumption for the production of such composites (13 – 54 MJ/kg for glass fibers, 76 – 80 MJ/kg for epoxy resins or 63 – 78 MJ/kg for polyester resins) it is urgent to research into recycling methods to recover glass fibres from the polymeric matrix in an energy-efficient manner and without affecting their mechanical properties, while revaluing the remains of resin without incurring additional energy costs or generating polluting agents [1]. The available strategies so far include the thermal (pyrolysis) and thermo-chemical (solvolysis) treatment of such G-FRP waste in order to promote fiber-resin separation and to take advantage of resin degradation to generate either a valuable organic oil or chemical building blocks of interest. G-FRP pyrolysis consists in applying a thermal treatment to the sample under oxygen-deprived atmosphere, which leads to the thermal cracking of the matrix fraction producing volatiles (pyrolysis oil and gas) and a solid residue of fibres, frequently covered by a layer of pyrolytic carbon. In a conventionally heated pyrolysis process, thermal energy is generated either by fossil fuels combustion or by joule effect, from which heat transfer takes place by convection, radiation and conduction. Given the low thermal conductivity of resins, conventional heating results in volumetric thermal gradients and, thus, in the need to heat the waste samples beyond their degradation temperature (450 – 700°C) to fully remove them from the fibers. As a result, the control of the products distribution from the pyrolysis of resins becomes limited, as higher temperatures promote eventually undesired thermal cracking reactions.

In this framework, microwave-assisted heating emerges as a potential solution to overcome traditional G-FRP pyrolysis limitations. The benefits of microwave-assisted thermal treating (from now on ‘MW-heating’) can be summarized into four main facts: i) drastically reduced processing times; ii) contactless and selective heating of target materials in complex sample mixtures; iii) induced temperature difference between the heated sample and the surrounding atmosphere and iv) energy efficiency increase with respect to traditional heating procedures with gas and/or steam. Furthermore, applied to G-FRP pyrolysis, MW-heating can provide: 1) enhanced control of thermal cracking products distribution and 2) lower degradation of mechanical properties for the recovered fibers thanks to the use of lower pyrolysis temperatures and processing times for a complete fibre clean-up. This also applies to G-FRP solvolysis: MW-heating could drastically reduce processing time and decrease sample temperature for a given resins conversion degree, thus, inducing a better control of chemical building blocks production and enhancing the preservation of the mechanical properties of the recovered fibres.

Based on this, the purpose of this work is to develop such MW-pyrolysis and MW-solvolysis solutions at bench scale (1 L reactor capacity) to recycle G-FRP waste samples aiming to: a) preserve the quality of the fibres as much as possible; b) get the most profitable output from the resins; c) validate the expected advantages of MW-heating systems over conventional ones for G-FRP recycling purposes.

## Experimental set-up and procedure

G-FRP pyrolysis and solvolysis tests were conducted at the two specific microwave oven cavities showcased in Figures 1a and 1b. The MW-pyrolysis oven consists of a 34 mm i.d. quartz tubular reactor inserted within a multimode MW cavity featured by a magnetron input power of 3.2 kW and four mode stirrers that homogenise the

electromagnetic field distribution within the cavity volume over processing time. The maximum attainable sample temperature is 1200°C. A quartz-transparent pyrometer connected to the oven allows sample temperature measuring and controlling. The treated sample is a mixture of pre-shredded G-FRP (2.5 mm long chips) and SiC particles (0.5 mm). SiC particles act here as inert MW-susceptor, i.e. dielectric material that is able to absorb MW irradiation and transform it into heat very efficiently, given the low MW-absorption capacity of both fibres and resins. The oil derived from resins pyrolysis is conducted through a traced line towards a condensers train for its collection. The solid residues are SiC particles, glass fibres and highly dehydrogenated carbon (char), which can be easily sieved out to recover each fraction. Pyrolysis trials were conducted under a moderate flow of N<sub>2</sub> (0.2 – 2.5 L<sub>STP</sub>/min) to avoid sample combustion and at different operating temperatures in the range 400 – 550°C to find the optimum temperature for product distribution and maximum fibres' mechanical properties recovery. The G-FRP : SiC weight ratio was varied in the range 1:2 – 1:10. On the other hand, the MW-solvolytic unit features a PTFE-lined 1L stirred-tank reactor. The sample, being a slurry containing pre-shredded G-FRP waste and a solvolysis agent, is heated by a 1.5 kW magnetron. The maximum operating temperature and pressure of such a system are 300°C and 199 bar, respectively. The temperature is monitored by a PTFE-lined thermocouple inserted within the fluid sample. Experimental trials for resins solvolysis were conducted at temperatures ranging 190 – 270°C, being the operating autogenic pressure dependant on the employed solvent and amount. Solvents include protic acids (acidolysis) and amino-based agents (aminolysis). Prior to every experimental test a pre-conditioning step is conducted, in which large blade parts are cut down, shredded and sieved into 2.5 mm parts. The chip (G-FRP) and core (balsa wood or polyurethane foam, mainly) are separated by flotation (Figures 1c and 1d).

## Results and discussion

Figures 1.e and 1.f show the appearance of the processed blade waste sample after a solvolysis treatment, starting from a feedstock consisting of shredded mixture of G-FRP, polyurethane foam (PUF), adhesives and coating lacquers. The recycling procedure applied in this specific case was MW-assisted aminolysis using tris (2-aminoethyl) amine, i.e. TREN, as solvent. This solvent was selected based on its proven effectiveness for the chemical recycling of PUF [2]. Results suggest that both bench scale MW-assisted pyrolysis and solvolysis reactors lead to complete separation of organic phase and glass fibres under the tested operating conditions. However, the nature of pyrolysis oils and solvolysis solutions is strongly dependant on the operating temperature, residence time and feedstock composition, employed solvent, solvent/G-FRP and MW-susceptor/G-FRP ratio.

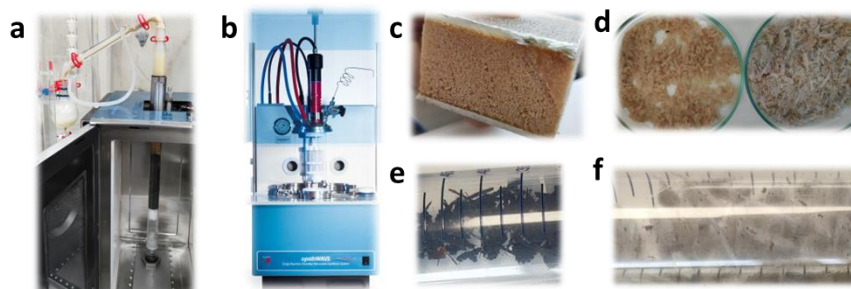


Figure 1. a) MW-pyrolysis reactor and oil recovery unit; b) MW-solvolytic stirred tank; c) blade waste part; d) sorted core (polyurethane foam) and chip (G-FRP); e) glass fibres after MW-aminolysis; f) isolated glass fibres after post-treatment (cleaning + filtering)

## Conclusions

The Europe-wide ban on landfilling of wind blades by 2025 increases the pressure on the need to develop solutions for the recycling of these materials in a sustainable way. This work addresses a novel experimental approach on the use of MW-heating to promote glass fibres recycling and resins valorisation via pyrolysis and solvolysis. Results suggest that an enhanced controllability on the organic products distribution can be attained based on the selective heating ability of MW irradiation.

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## References

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