

Characterization of the products from waste wind turbine blades thermal utilization

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ABSTRACT

The development of renewable energy is related to the growing share of wind energy in the worldwide balance. Assuming the average lifetime of wind turbines is about 20 years, an avalanche-growing amount of waste in the form of used wind turbine components should be expected. Their disposal will become a challenge. The aim of this study is to indicate the energy potential of the utilization of wind turbine blades by pyrolysis method with the simultaneous production of gaseous and liquid fuels and the possibility of recovering raw materials in the form of carbon and glass fibers. The results show that over 50% of the initial mass of the pyrolyzed waste wind turbine blades can be turned into gaseous and liquid products. These products have a high calorific value (ca. 30 MJ/kg) which is more than sufficient to sustain the pyrolysis process. Additionally, the product stream contains high concentrations of ethylene, propylene, and phenol, which could be valuable products once separated. The recovered fibers are covered with carbonaceous material, which necessitates a post-oxidation process for their effective utilization. Furthermore, the high temperature of the pyrolysis process (600 °C) likely causes degradation of the mechanical properties of the glass fibers. These challenges highlight the necessity of addressing the limitations associated with fiber recovery, including the removal of carbonaceous residues and the preservation of fiber quality. By discussing these constraints, the study provides a more comprehensive overview of the findings, offering insights into both the potential and the challenges of using the pyrolysis method for the disposal and recycling of wind turbine blades.

Keywords: waste, pyrolysis, pyrolytic gas, fibers.

INTRODUCTION

Among many renewable energy sources, wind energy has a major share in the energy market. A prominent example is a European scenario where the amount of energy produced by wind turbines subsidizes only to natural gas, and the wind industry is ranked as the fastest-growing energy source (Paulsen & Enevoldsen, 2021). However, this trend is now followed in USA, China, and other regions (Cooperman et al., 2021). Despite significant progress in wind energy adoption, a key challenge remains unresolved: the management of waste generated by wind turbine blades (WTBs), particularly through effective recycling. This

study focuses on addressing this challenge by analyzing the energy potential of by-products derived from pyrolysis of WTBs, a recycling method that has received growing attention due to its advantages over mechanical and chemical alternatives. Unlike previous studies, the current research provides a more detailed characterization of gaseous and liquid products obtained during pyrolysis and evaluates their energy recovery potential.

In general, the recently installed wind power capacity worldwide is 743 GW (GWEC, 2017), yet it is expected to reach ca. 5040 GW in 2050 (IRENA, 2019). On the other hand, this increase in wind energy role will generate cumulatively 43.4 million tons of wind turbine blade (WTB)

waste by 2050 (Liu & Barlow, 2017). While this perspective is rather long-term, the problem of waste blade disposal is raised presently (Cooperman et al., 2021; Liu & Barlow, 2017; Ramirez-Tejeda et al., 2017), as the wind turbines from the early 2000s boom are reaching their lifetime (Cooperman et al., 2021). The blades are the most problematic part of a wind turbine as they are composed of glass or carbon-fiber-reinforced polymers (GFRP or CFRP). The share of the composite in the blade is ca. 80–90%, of which 60–70% is fibers and 30%–40% is resin (Jensen & Skelton, 2018). The resins are usually high-grade epoxy or polyester (Liu & Barlow, 2017). Besides the composites, the blade may consist of balsa wood, foam, steel fasteners, copper or aluminum lightning protections, and adhesive (Justine Beauson & Brøndsted, 2016; Cooperman et al., 2021; Ramirez-Tejeda et al., 2017).

The inability to effectively separate composite materials remains the core issue in WTB disposal. However, it should be noted, that the use of composite materials is now very common, and in some fields, composites have almost completely replaced traditional materials due to their lightness, durability, and strength, e.g. in the construction of parts of airplanes, cars, boats, skis, etc. (Åkesson et al., 2013; Błędzki et al., 2021; Liu & Barlow, 2017; Oliveux et al., 2015). In many applications composites are also more economical than traditional materials, so the problem of disposal of this type of materials is much wider than just turbine blades. In general, the methods of recycling WTBs can be divided into three groups: mechanical, chemical, and thermal methods (Ge, Li, et al., 2023; Paulsen & Enevoldsen, 2021). Detailed descriptions of these methods are presented in many comprehensive articles considering the problem of waste turbines and composites utilization (Beauson et al., 2022; Cooperman et al., 2021; Fonte & Xydis, 2021; Jensen & Skelton, 2018; Karuppanan Gopalraj & Kärki, 2020; Krauklis et al., 2021; Oliveux et al., 2015; Paulsen & Enevoldsen, 2021; Ramirez-Tejeda et al., 2017; Yang et al., 2022). In short, in the case of mechanical processing, by grinding and shredding, a product rich in resins and fibers is obtained, which can be used in other processes as a filling or reinforcing material (Mattsson et al., 2020). However, the process results in reducing the fibers' stiffness, and the fibers usually contain some resins in the end, which limits their application (Cooperman et al., 2021; Xu et al., 2023).

Among chemical methods, the most common one is called solvolysis. This process involves waste treatment with a solvent, e.g. alcohols, water, or ketones, in increased pressure and temperature. The main problem of the method is that a high temperature can degrade fiber properties and that process parameters variate depending on the processed material (Paulsen & Enevoldsen, 2021). Another problematic issue of solvolysis is solvent recovery (Xu et al., 2023). Finally, the thermal methods include pyrolysis and incineration. During the thermal processing of composites, the temperature of the process is important, as high temperature reduces the mechanical strength of the recovered fibers. Combustion requires appropriate preparation of the material (grinding) and should be carried out at a low temperature, e.g. in a fluidized bed (Naqvi et al., 2018).

The pyrolysis process (thermal (Xu et al., 2023) or microwave (Åkesson et al., 2012)) conducted in the absence of oxygen makes it possible to separate the polymer matrix from the fibers and convert it into a combustible gas. Also in this case, if further use of glass fibers is planned, the temperature of the process should be controlled and chosen carefully, as it might result in fiber degradation. Generally, a temperature of ca. 500–550 °C is required to decompose resins (Cunliffe et al., 2003; Giorgini et al., 2016; Paulsen & Enevoldsen, 2021). At the same time, a temperature of over 450 °C can significantly reduce fiber strength, with the degradation rate increasing with the temperature (Feih et al., 2011).

Pyrolysis has emerged as the most promising method for wind turbine blade (WTB) recycling, despite certain challenges associated with its application. This process is highly regarded for its ability to produce high-value products while minimizing material degradation, a critical factor in ensuring the effective recovery of resources. Such benefits are particularly significant as they align closely with the principles of the circular economy and the broader objectives of sustainable development goals. One of the primary advantages of pyrolysis is its capacity to generate a combustible gas, which can be utilized to sustain the process itself or for various other energy applications (Xu et al., 2023). This self-sustaining feature enhances the overall energy efficiency and economic viability of the process. Additionally, pyrolysis is recognized as a mature and well-established technology that offers a favorable balance between relatively low investment costs and the high value

of the recovered products (Paulsen & Enevoldsen, 2021). These attributes further solidify its position as a leading solution for the utilization of end-of-life wind turbine blades, addressing both economic and environmental challenges.

The paper presents the results of laboratory tests commissioned by the Norwegian company Gjenkraft AS (Høyanger, Norway), which deals with the development of waste wind turbine blades recycling technology, enabling the production of glass and carbon fibers with minimal degradation of their parameters. Recycled fibers are used to produce new products based on composites. The current study uniquely focuses on demonstrating the energy potential of pyrolysis by-products gaseous and liquid fuels while assessing their properties in detail. Therefore, the main goal was to characterize the liquid and gaseous products obtained during the process.

MATERIAL AND METHODS

Process of pyrolysis

Pyrolysis tests were performed using a laboratory-scale batch pyrolyzer (Fig. 1), heated by a mantle made of three band heaters installed on the side walls of the reactor. A sample of the blade residues was placed in a basket at the center of the reactor, together with a thermocouple measuring the temperature inside the sample bed. The process temperature was set from ambient to 600 °C. The sample bed temperature was measured using a 1st class K-type thermocouple and a digital recorder. To ensure an inert atmosphere in the reactor, a constant flow of nitrogen (3 L/min) was passed through the reactor. The pyrolysis test lasted approximately 30 minutes.

The gas samples were taken from the top of the reactor and passed through a series of impinger bottles filled with isopropanol to capture tars and clean the gas before analysis. The first impinger bottle was installed as close as possible to the reactor's top to minimize the length of the Teflon hose and reduce the loss of collected condensates. The second impinger bottle was immersed in a PLC-controlled cooling bath SD 07R-20 (Poly-Science, USA). The bath was filled with ethylene glycol, and the temperature was set to -5 °C. The final bottle was filled with a silica gel bed, which removed residual moisture and tar. After leaving the series of impinger bottles, the dry, cooled gas

was directed through an external pump, which facilitated gas sampling and introduced it into an analyzer. The analyzer GAS 3100R SYNGAS (Atut, Poland) was used to determine the concentration of key permanent gases (H_2 , CO , CO_2 , CH_4 , C_nH_m , O_2). Measurements were conducted online throughout most of the process.

Sample preparations

Additionally, three gaseous samples were collected into Tedlar's bags for gas chromatography (GC) analyses of light hydrocarbons. These analyses were performed using a GC (HP 6890) equipped with a flame ionization detector (FID) and a Restek Alumina BOND KCl column. The qualitative analysis of gaseous compounds in the samples was based on the standard chromatogram of the column, prior measurements, and gaseous standards. The quantitative analysis was calibrated using a prepared methane curve. Hydrogen was used as the carrier gas for GC-FID. For qualitative analysis, the temperature program was set to 1 minute at 40 °C, followed by a temperature increase to 200 °C at 10°C/min, with a final hold at 200 °C for 3.5 minutes. Quantitative analysis maintained a constant temperature of 100 °C for 10 minutes.

In addition, the gaseous samples were analyzed using GC-MS (Agilent 7820-A chromatogram and Agilent 5977B MSD, USA). The GC was equipped with an HP-5 column. The inlet operated in split mode (50:1), and the temperature program was set to 40 °C for 10 minutes with helium as the carrier gas. The purpose of this analysis was to confirm the presence of volatile hydrocarbons heavier than C_4 , which could not be detected using the Restek Alumina BOND KCl column.

Chemical analysis

Samples of the solutions from the impinger bottles were analyzed using GC-MS (Agilent 7820 with MSD 5877B). The qualitative analysis employed an HP-5MS column in split mode (20:1) with helium as the carrier gas. The temperature program started at 50 °C for 5 minutes, followed by a temperature increase of 5 °C/min until reaching 250 °C, and then another increase of 10 °C/min until the final temperature of 300 °C, which was maintained for 5 minutes. Compound identification was performed automatically by comparing mass spectra with the NIST-14 MS library.

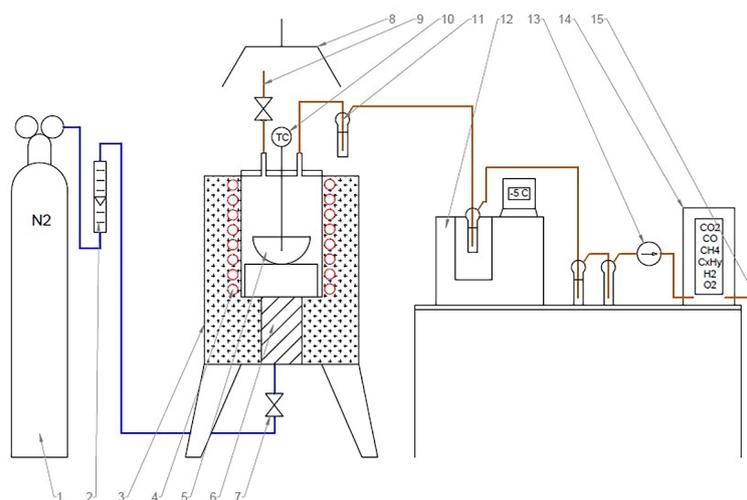


Figure 1. Test rig diagram. 1 – nitrogen bottle, 2 – rotameter, 3 – pyrolyzer, 4 – band heaters, 5 – sample basket, 6 – mixing zone, 7 – valve, 8 – gas extractor, 9 – gas outlet, 10 – thermocouple, 11 – impinger bottle, 12 – cooling bath, 13 – external pump, 14 – analyzer, 15 – sample outlet

Material

The fed material, waste blades from wind turbines, was provided by the Norwegian company Gjenkraft AS. Wind turbine blades, like other advanced composite materials, are inherently heterogeneous and consist of various sections fulfilling distinct structural roles. To address this complexity, a sampling strategy was developed based on a visual assessment to identify the most prominent and distinct components present in significant quantities. Three representative material types were selected for analysis, as presented in Table 1 and illustrated in Figure 2. These materials were further characterized using FTIR/TGA analysis performed in an external laboratory (Department of Engineering and Technology of Polymers, Wrocław University of Science and Technology), revealing their likely composition as epoxy resin (sample no 1), polyurethane resin (sample no 2), and a filled silicone elastomer (sample no 3). Although additional minor components,

such as wires, were observed, the selected fractions represent the dominant materials within the WTB waste stream. This approach ensures that the analysis focuses on the key constituents while providing insight into the material behavior during pyrolysis.

RESULT AND DISCUSSION

Solid product analysis

After pyrolysis of feedstock, a product largely devoid of organic parts was obtained (Fig. 3). From the initial weight of 540 g, only 250 g of the product remained, which means that ca. 53% of the waste was turned into gases. The glass fiber recovered in this way has a characteristic black color due to the presence of soot and heavy tars that remain in the material. A post-oxidation process would be required to remove the carbonaceous material (Xu et al., 2023).

Table 1. Higher heating value and ultimate analysis of the selected samples

| Test | Symbol | Sample value | | | Unit | Standard procedure |
|----------------------|----------------|--------------|------|------|-------|--------------------|
| | | 1 | 2 | 3 | | |
| Higher heating value | HHV | 29.6 | 22.4 | 23.5 | MJ/kg | EN 14918:2009 |
| Carbon content | C ^d | 64 | 59.3 | 20.5 | % | EN ISO 16948:2015 |
| Hydrogen content | H ^d | 3.8 | 6.1 | 4.2 | % | EN ISO 16948:2015 |
| Nitrogen content | N ^d | 3.1 | 4.2 | 0.04 | % | EN ISO 16948:2015 |
| Sulfur content | S ^d | 0.27 | 0.65 | 0.37 | % | EN ISO 16994:2016 |

Note: d – dry basis.

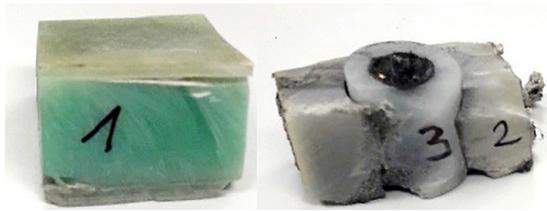


Figure 2. Selected samples and their identification numbers

A comparison of basic parameters of the raw WBT and pyrolyzed is presented in Table 2. It should be noted, that due to the heterogeneity of the raw material, the values of the parameters are given as a range of results that were obtained for six samples. The solid product of pyrolysis was much easier to shred and grind. As a result, a much more homogenized sample was obtained. However, the standard deviation of the mean from six samples of pyrolyzed material that was analyzed is still significant.

The results in the table show that despite the relatively high temperature of pyrolysis, some of the organic material remained in the solid residue

(VM = 8%) which indicates that not all organic material was completely degraded during pyrolysis. This residual organic content may offer additional energy potential if post-oxidized, however, it also suggests inefficiencies in the process that need to be optimized to maximize recovery. The increase of ash content in the solid residue indicates that it contains mainly glass fiber. However, the carbon content (24 %) only confirms what was presented in Figure 3 (right) – that the fibers are covered with nonvolatile soot and tar that is produced during pyrolysis. This coating negatively impacts the mechanical properties and recycling potential of the fibers, necessitating post-processing such as oxidation. Once cleaned, these recovered fibers could find application in low-demand sectors such as insulation materials or as fillers in polymer composites.

The effect of pyrolysis on the composite's glass fibers was also investigated with the use of SEM with EDS. From the pyrolyzed sample (Fig. 3), the two most frequently repeated and characteristic structures were selected to analyze. The first one is in alternating order with long fibers



Figure 3. Photos of the feedstock (left) and pyrolyzed material (right)

Table 2. Proximate and ultimate analysis of the samples before (raw) and after pyrolysis

| Test | Symbol | Value | | Unit | Standard procedure |
|-----------------------------------|-----------------|-----------|-----------|-------|---------------------|
| | | Raw | Pyrolyzed | | |
| Weight | M | 540 | 250 | g | – |
| Moisture content ¹ | MC | 0 | 0 | % | EN ISO 18134-2:2015 |
| Volatile matter content | VM ^d | 43–57 | 8±1 | % | EN 15148:2009 |
| Ash content | A ^d | 35–58 | 82±10 | % | EN ISO 1822:2015 |
| Higher heating value ² | HHV | 21.2–28.2 | – | MJ/kg | EN 14918:2009 |
| Carbon content | C ^d | 36–64 | 24±4 | % | EN ISO 16948:2015 |
| Hydrogen content | H ^d | 2.9–3.8 | 0.6±0.1 | % | EN ISO 16948:2015 |
| Nitrogen content | N ^d | 1.8–3.1 | 2.6±0.2 | % | EN ISO 16948:2015 |
| Sulfur content | S ^d | 0.2–0.3 | 0.04±0.02 | % | EN ISO 16994:2016 |

Note: 1 – wet basis, 2 – calculated using the formula from the standard, d – dry basis.

and no visible tar residue on the surface (Fig. 4 – left and Fig. 5), and the second with short disordered fibers that are caked with tar residues (Fig. 4 – right and Fig. 6). Table 3 presents EDS results from the regions presented in Fig. 7 and Fig. 8.

It should be noted, the marked region of the ordered structure involves well-purified fibers (they are white in Fig. 4), and it can be seen that

the content of carbon is much smaller (Table 3) than in the case of the structure covered with carbonaceous material (as seen in Figures 6 and 8).

The SEM analysis reveals fiber damage including possible shortening and surface cracks which is primarily due to thermal degradation during the pyrolysis process. Elevated temperatures can significantly reduce the tensile strength of glass fibers.



Figure 4. Photography of pyrolyzed samples: straight fiber composite (left) and disordered fiber composite with heavy hydrocarbons present on the surface (right). Red marks refer to Figure 5 and Figure 6.
Picture magnification: ~3×

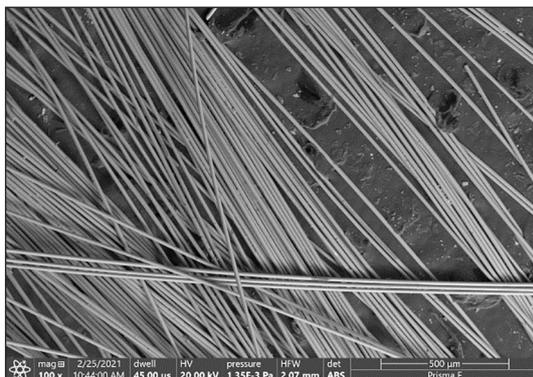


Figure 5. Straight fibers composite (a red marked region on the left of Fig. 4), picture magnification: 100×

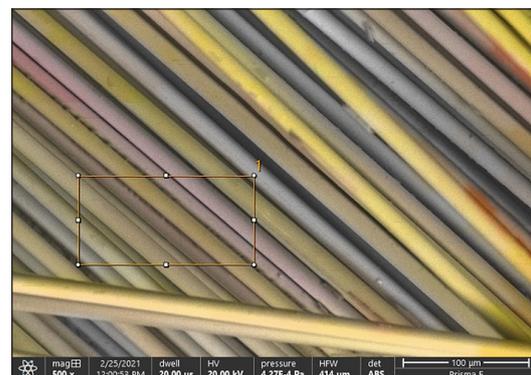


Figure 7. Straight fibers composite with a marked region for EDS analysis. Picture magnification: 500×

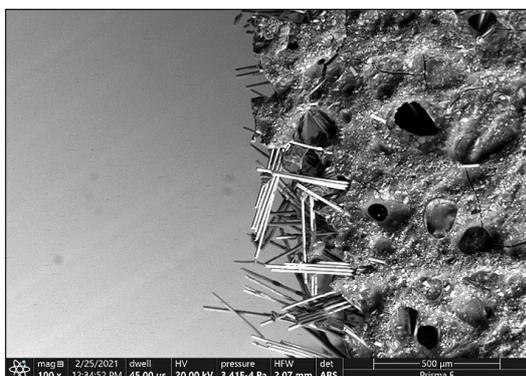


Figure 6. Disordered fibers composite (a red marked region on the right of Fig. 4), picture magnification: 100×

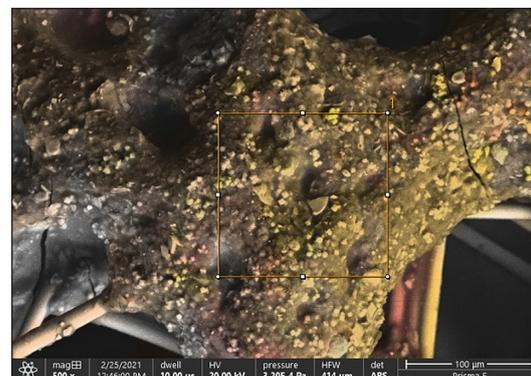


Figure 8. Disordered fibers composite with a marked region for EDS analysis. Picture magnification: 500×

Table 3. Average elemental composition from EDS analysis for the marked regions (in Figures 7 and 8)

| Element | Ordered (Fig. 7) | Disordered (Fig. 8) |
|---------|------------------|---------------------|
| C | 7.1 | 46.5 |
| O | 44.8 | 26.8 |
| N | – | 13.3 |
| Si | 20.9 | 8.0 |
| Ca | 19.9 | 1.3 |
| C | 7.1 | 1.4 |
| Al | 5.5 | 2.6 |
| Mg | – | 1.5 |

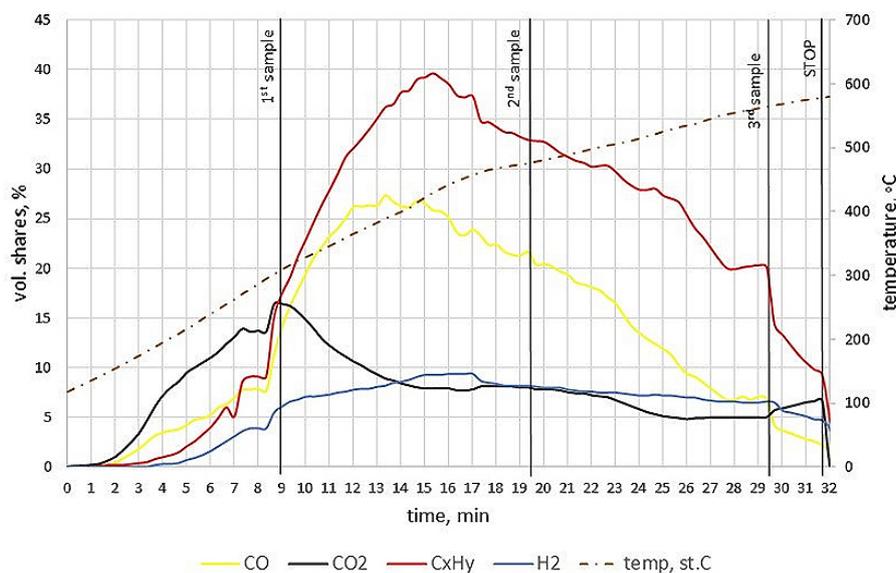
For instance, studies (Jenkins et al., 2015) have shown that exposure to high temperatures leads to a substantial decrease in fiber tensile strength. High temperatures above 550 °C, as reported in previous studies (Feih et al., 2011; Paulsen & Enevoldsen, 2021; Yang et al., 2012), can weaken the fiber structure, while grinding causes mechanical fragmentation. This degraded condition limits the reusability of the fibers in high-strength applications, but they may still be utilized in lower-performance applications, such as construction materials or non-structural components.

Combining the EDS results (Table 3) with presented pictures proves that post-pyrolysis solid product would require further oxygenation to make the recovery of the fibers applicable. The required post-oxidation process, however, has important economic and environmental implications. Economically, it introduces additional

costs associated with energy consumption and infrastructure requirements. Yet, the process significantly increases the quality and market value of the recovered fibers, which could make them suitable for reuse in diverse applications, such as composites. Environmentally, while post-oxidation increases energy demand and CO₂ emissions, it ensures the removal of harmful residues, like soot and heavy tars, improving the safety and usability of the final by-product. If the carbonaceous material is oxidized efficiently, using heat or gases generated during pyrolysis, these impacts could be partially mitigated, enhancing the overall sustainability of the process.

Gas analysis

Figure 9 presents changes in the gas composition during the pyrolysis process. The figure presents only the products derived from pyrolysis without nitrogen that was used to provide an inert atmosphere in the reactor. It should be noted that the “C_xH_y” presented in the figure corresponds to all the hydrocarbons in the gas (including CH₄) but these values should be treated rather like an indicator than a precise measurement. This is because the used analyzer is overburdened with a high error when the concentration of hydrocarbons other than CH₄ exceeds 10% v/v (as it is beyond the measurement range). To make more precise measurements the gas was sampled three times during the process (presented as vertical lines in Figure 9) and measured with the use of

**Figure 9.** Gas composition changes during the process

GC-FID. Table 4 presents the composition of the hydrocarbons collected in Tedlar’s bags and analyzed with the use of GC-FID. Besides methane, the gas also includes significant shares of ethane, ethylene, and propylene. Smaller shares can be attributed to propane and C₄ compounds. In general, the GC-FID analysis revealed over 20 compounds but most of them have an insignificant share. The GC-MS analysis revealed that these compounds include C₄-C₆ isomers, like 1,3-pentadiene, 3-penten-1-yne, cyclopentene, 1,3-cyclohexadiene, and 1-hexene. Additionally, Table 4 also includes measurements of H₂, CO, and CO₂ that correspond to the time when the samples were collected. The “rest” in the table was calculated as a difference between 100% and all the quantified components. It mostly includes nitrogen and negligible amounts of oxygen and other hydrocarbons. It should be noted that the gas composition presented in Table 4 includes only permanent and very volatile gases. All the condensable compounds (heavier hydrocarbons) were separated in the impinger bottles. Due to this approach, it is hard to determine the exact yield of permanent gaseous product and condensable vapors. However, based on the yield of solid residues (Table 2) it can be concluded that the share of volatiles (gases and condensable vapors) is ca. 50%.

If the nitrogen would be excluded from the mixture, as it shouldn’t be necessary for an industrial process, the gas composition, for sample 2, would have a composition as in Figure 10. The obtained gas has a high HHV (ca. 30.4 MJ/nm³ or 29.0 MJ/kg). It’s significantly higher than in the case of biomass-derived pyrolytic gas, which has a much

higher share of CO₂ and CO due to the high content of oxygen in almost any biomass (Glushkov et al., 2021; Griessacher et al., 2012). The WTB-derived gas has a noticeably high share of ethylene and propylene. Both are valuable subtract in polymers formation and could be valuable products of WTB pyrolysis. The gas composition and the HHV of the obtained gas resemble the parameters of the gas obtained from another problematic waste that consists of polymers – tires (Czajczyńska et al., 2022).

Liquid product analysis

The liquid fraction which includes condensing hydrocarbons was collected in impinger bottles filled with isopropanol. The obtained mixture had a dark color and was thick and sticky. The impinger bottles with the mixture are shown in Figure 11. Figure 12 presents a GC-MS chromatogram of the liquid sample. The tests show that the liquid sample includes dozens of compounds among which 60 were identified based on their mass spectrum. In general, condensable compounds are aromatic. These include benzene, substituted benzene compounds (e.g. toluene; benzene, 1,3-dimethyl, styrene, xylenes), heteroatomic aromatic structures including oxygen and nitrogen (e.g. pyrrole, pyridine, pyrazine, phenol), two-ring aromatics - including substituted one and heteroatomic (e.g. naphthalene, indene, benzofuran), 3 and 4-ring aromatic structures (e.g. acenaphthylene, phenanthrene, anthracene).

Figure 13 presents the areas of the 15 biggest peaks that sum up to ca. 80% of the total area of all the peaks. It should be noted that the area of

Table 4. Composition of C₁-C₄ hydrocarbons in the collected samples

| Compound | | Sample 1 | Sample 2 | Sample 3 |
|-------------------------------|-----------------|----------|----------|----------|
| | | vol., % | | |
| CH ₄ | Methane | 8.6±0.2 | 26.2±0.2 | 13.9±0.2 |
| C ₂ H ₆ | Ethane | 1.3±0.1 | 2.6±0.3 | 1.6±0.2 |
| C ₂ H ₄ | Ethylene | 3.4±0.3 | 7.0±0.7 | 2.4±0.2 |
| C ₃ H ₈ | Propane | 0.3±0.1 | 0.3±0.1 | 0.2±0.1 |
| C ₃ H ₆ | Propylene | 2.3±0.2 | 2.1±0.2 | 1.0±0.1 |
| C ₄ H ₈ | Butenes | 0.2±0.1 | 0.2±0.1 | 0.2±0.1 |
| C ₄ H ₆ | 1,3-butadiene | 0.1±0.1 | 0.2±0.1 | 0.1±0.1 |
| Sum of hydrocarbons | | 16.2±1.1 | 38.6±1.7 | 19.4±1.0 |
| | H ₂ | 5.5±1.2 | 8.2±1.2 | 6.6±1.2 |
| | CO | 11.4±1.2 | 21.7±1.2 | 6.9±1.2 |
| | CO ₂ | 16.4±0.6 | 8.0±0.6 | 5.0±0.6 |
| | Rest | 50.5 | 23.5 | 62.1 |

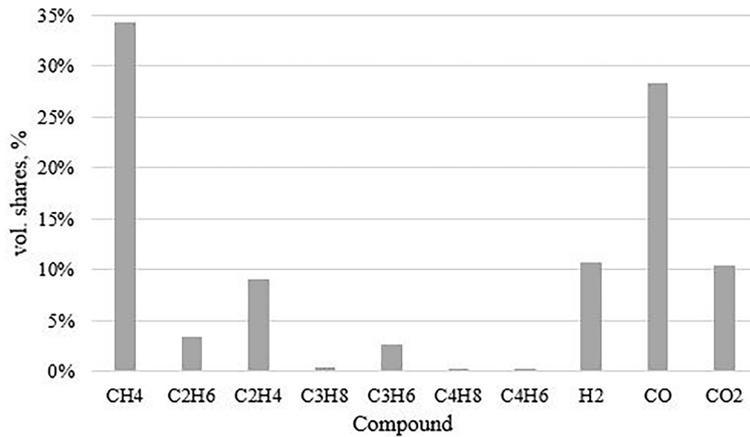


Figure 10. Exemplary composition of the gas for the 2nd sample with nitrogen exclusion



Figure 11. Impinger bottles with the isopropanol-liquid fraction solution

the peak, while proportional to the concentration of the compound, maybe differ for different compounds and temperatures. Nevertheless, this simple comparison informs, with high probability,

which compounds dominate. Based on the liquid composition, it can be assumed that the liquid fraction's lower heating values (LHV) are somewhere between crude oil products and alcohols. For example, the calorific value of benzene or toluene is 40.2 MJ/kg and 40.6 MJ/kg, respectively. Slightly less caloric (due to oxygen content) are phenolic compounds, e.g. phenol – 32 MJ/kg, cresols – approx. 34 MJ/kg.

Comparison with literature results

With many components involved and changes in production technology, wind turbine blades can be different in their composition. Therefore, the obtained products may have different compositions as well. This issue was clearly indicated in the work of Lichao Ge et al. (Ge, Xu, et al., 2023) which investigated liquid and gaseous products from pyrolysis of waste wind turbine blades' basic

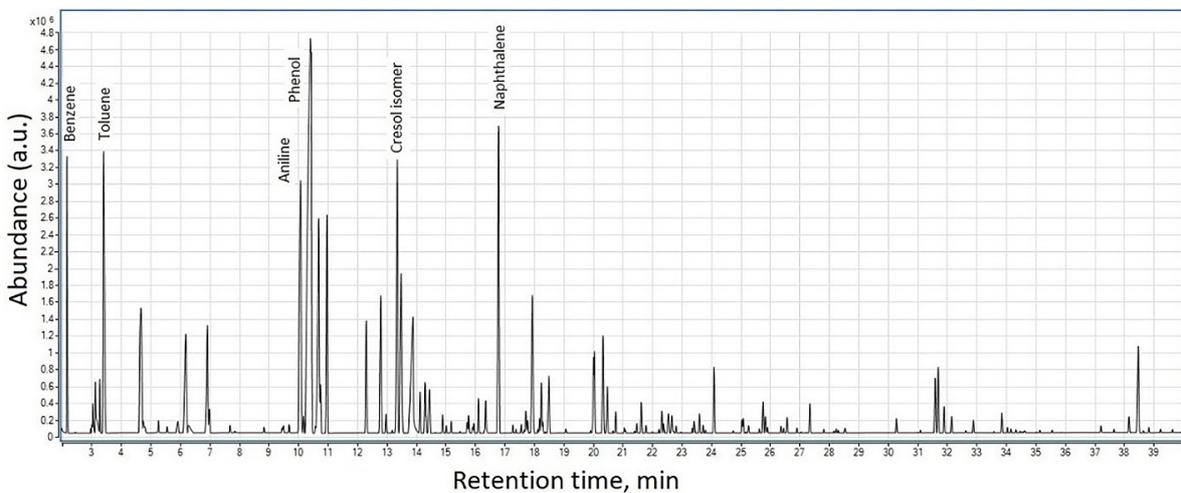


Figure 12. Chromatogram of the liquid sample

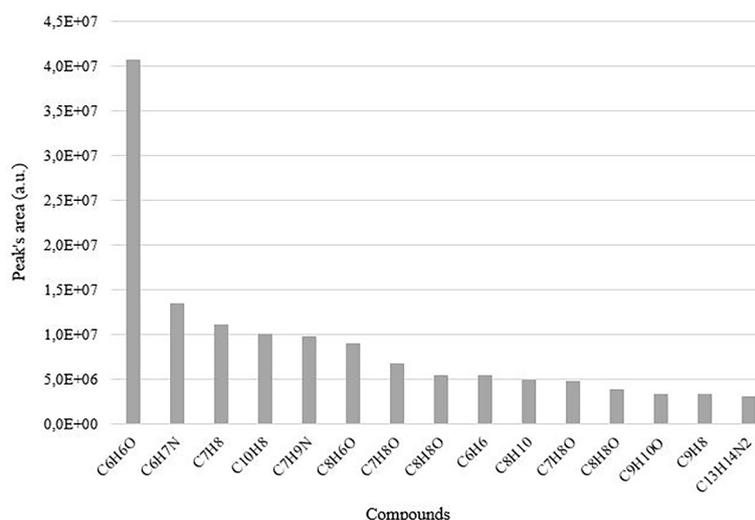


Figure 13. Main compounds of the liquid sample C₆H₆O – phenol, C₆H₇N - aniline or methylpyridine, C₆H₇ – toluene, C₁₀H₈ – naphthalene, C₇H₉N – toluidine isomer, C₈H₆O – benzofuran, C₇H₈O – cresol isomer, C₈H₈O – 2,3-dihydrobenzofuran, C₆H₆ – benzene, C₈H₁₀ – xylene isomer, C₇H₈O – cresol isomer, C₈H₈O – styrene, C₉H₁₀O – p-isopropenylphenol or 2-methyl-2,3-dihydrobenzofuran, C₉H₈ – indene, C₁₃H₁₄N₂ – benzenamine, 4,4'-methylenebis

components, i.e.: epoxy resin, thermoplastic polyurethanes, and glass and carbon fibers. Each of these groups gave different gas composition. A noticeable amount of hydrogen, ca. 6 % v/v, was produced only in the case of glass fiber. At the same time, the high content of C₂-C₃ hydrocarbons was typical for epoxy resins. These two attributes, hydrogen and C₂-C₃ hydrocarbons presence, were also observed in our case. Therefore, the results from the work of L. Ge et al. are convergent with ours as the majority of our sample included epoxy resins and glass fibers. Interestingly, the oil composition is significantly different, despite very similar process conditions, i.e. 600 °C and constant purge with nitrogen. While in the work of Licaho Ge et al., phenol was also one of the main components, just as in our case, the main product was bisphenol A. In our case, bisphenol A was not among the identified compounds. On the other hand, we detected a significant amount of aromatic hydrocarbons (e.g. benzene, toluene, naphthalene), which were not found in the work of Licaho Ge et al. The reason for this difference might have come from the interaction of the vapors with the solid residue. In the case of the work of L. Ge et al., the sample was small (10 g) and it was pure epoxy resin with no glass fibers. In our case, the sample was 540 g of mixed material containing glass fibers. As the material was in the form of a pile, most of the produced vapors had to pass through the hot residual

solid containing char and fibers. This would prolong the residence time in a high temperature and the mixture of char and fibres could have acted as a catalyst (Bu et al., 2022; Zhang et al., 2023). As a consequence, the decomposition and deoxygenation of the vapors might have been much deeper, resulting in no bisphenol A and a noticeable share of aromatic compounds. A similar dominance of bisphenol A and phenol, with a negligible share of aromatic, was indicated in the work of Wangmi Chen et al. (2023). Although this work involved a crushed and mixed sample of a waste wind turbine blade, the amount of the sample was again much lower than in our case (5 g vs. 540 g). This could partly support the hypothesis of a catalytic role of the char. However, while the investigated sample was a mixed blade's components, it still might have been different than the sample used by us. For instance, in the work of W. Chen, the sample was characterized by the ash and volatiles content of 25.1% and 23.57%, respectively. In our case, the sample had ash content varying between 35–58%, and the volatiles ranging from 43% to 57%. This indicates that the sample might have different composition that resulted in different products. This also affected the share of the products. In our case, the oil and gas share was ca. 50%. In the work (Chen et al., 2023) the share was ca. 21%. This can be explained by the significant difference in the volatiles content, which are transformed into gases and vapours.

CONCLUSIONS

The conducted research showed that pyrolysis of WTBs at 600 °C results in ca. 50% conversion of solid feedstock into gaseous and liquid fractions. These fractions have a high calorific value of over 30 MJ/kg. Assuming that pyrolysis energy consumption is ca. 2 MJ/kg (Daugaard & Brown, 2003), this means that WTBs pyrolysis should be easily self-sustained (the energy output from 1 kg of WTBs would be ca. 15 MJ). However, this simple calculation did not include soot that was covering the glass fibers. If oxidized, it should provide an additional pool of heat energy. The recovered fibers, although degraded, could be another product, next to the heat, of the process. Moreover, the results show that the pyrolytic gas contains a noticeable share of light olefins, i.e. ethylene and propylene. Both are crucial feedstocks in the petrochemical industry (with ethylene demand alone being 170 million tons per year (Zhang et al., 2019) and are regarded as valuable products. However, the cost of their separation should be seriously considered along with the potential application of other gaseous products (e.g. H₂). These products would require separation as well and could make the process more profitable. Nevertheless, separation of such a complex mixture would probably have to apply cryogenic methods due to the presence of ethane (Zhang et al., 2019). The produced liquid fraction contains a complex mixture of mainly benzene and phenol derivatives. It seems that phenol is the dominant compound in the liquid fraction mixture and it could be another product obtained after separation. In such a case, this could be considered as a partial recycling process as phenol is commonly used in production of resins – like those used in wind turbine blades. In contrary to demanding separation of gaseous products, separation of the liquid products could be based on distillation processes with the heat provided from combustion of less valuable pyrolysis products, e.g. char or methane. Regardless of the products and their application, the result proved that pyrolysis might be a good solution for WTBs utilization. Moreover, the comparison with other works on waste turbine blades pyrolysis showed that the material can vary in its composition and that might strongly affect the obtained products. It is also hypothesized that the presence of char/fiber residue in the reactor can act catalytically on the vapors, however, proving this requires further research.

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