EXPLORING RECYCLING OF COMPOSITES USING HIGH-VOLTAGE FRAGMENTATION

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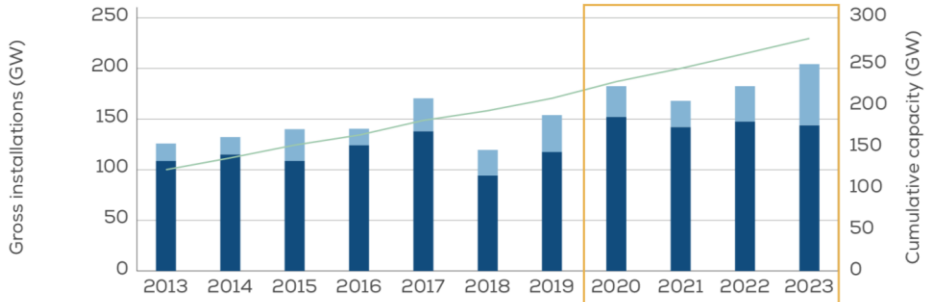
Introduction

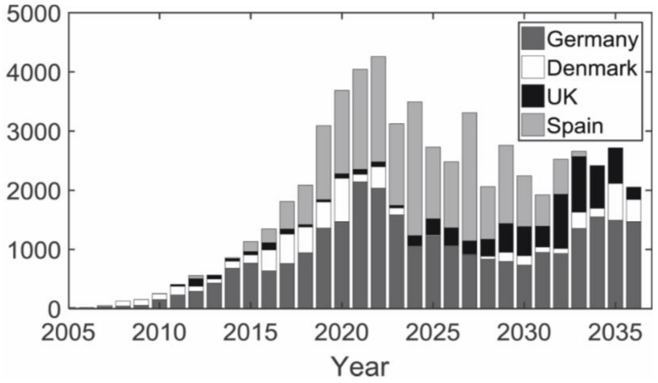
FIGURE 1
Gross annual installations in Europe



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Offshore	1.5	1.5	3.0	1.6	3.2	2.7	3.6	2.9	2.7	3.4	5.9
Onshore	11.0	11.6	10.9	12.3	13.9	9.4	11.7	15.2	14.2	14.7	14.5
Cumulative	122	135	148	162	178	190	205	222	238	255	275

Source: WindEurope

Number of onshore wind turbines reaching 20-years of operation annually[1]



[1] Renewable and Sustainable Energy Reviews, Volume 82, Part 1, February 2018, Pages 1261-1271

WindEurope estimated around 14,000 blades could decommissioned by 2023, equivalent to between 40,000 and 60,000 tons. Recycling these old blades is a top priority for the wind industry.

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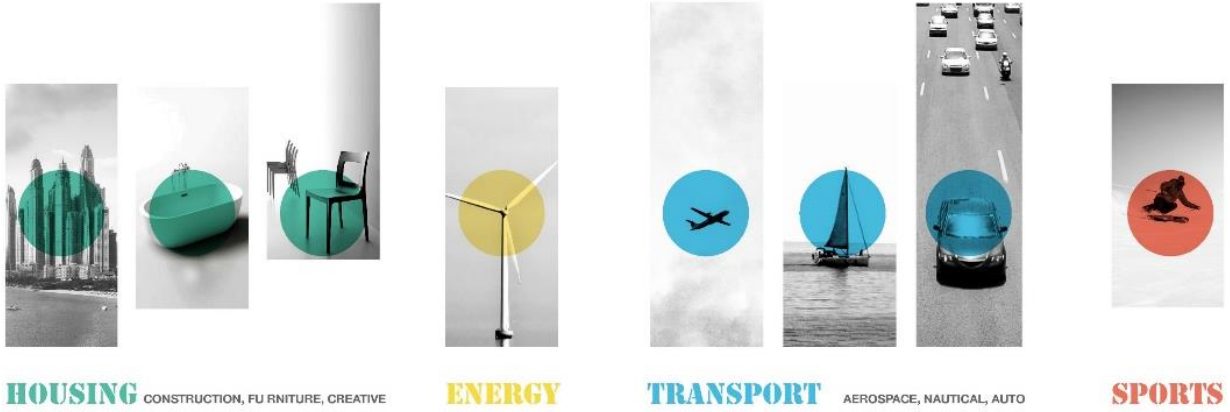
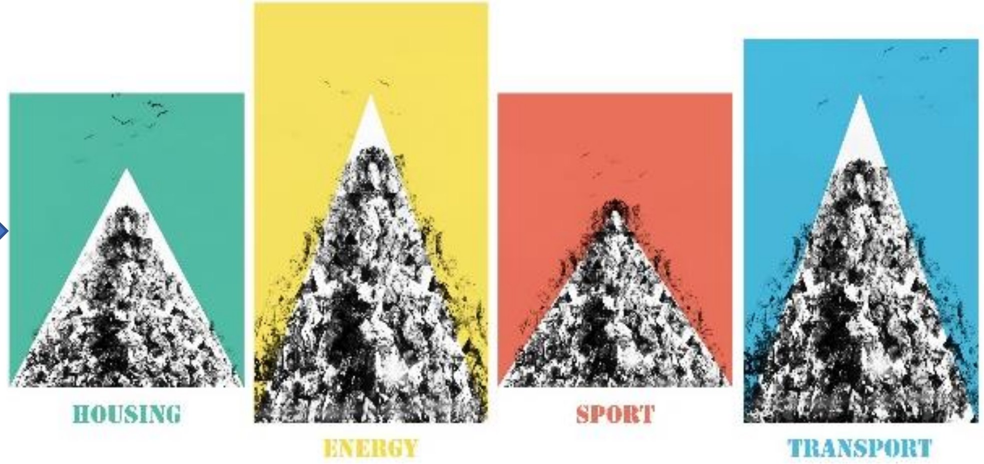
Introduction



Fiber-Reinforced Plastics (FRPs) are widely adopted in **several massively used products** in the electronics, sport equipment, medical equipment, automotive, construction, wind energy, aeronautics and marine industries, due to their better lightweight and corrosion resistance compared to metals.

The **recovery** of plastics and fibers after the use phase of such products **is a challenge**.



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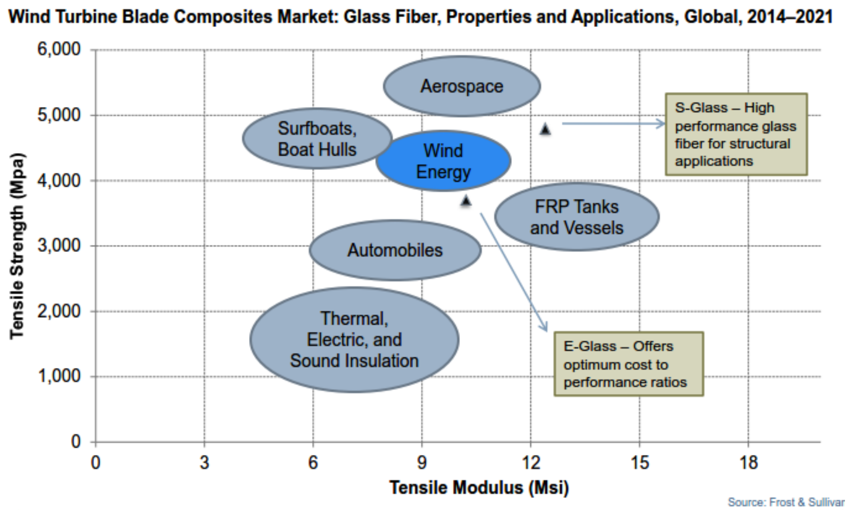
Motivation: the cross-sectorial approach

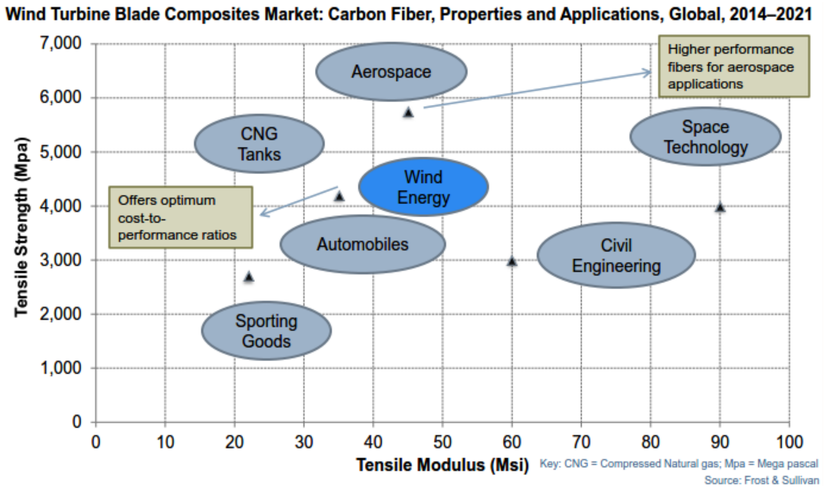
Composite **re-use** would support **price reduction**.
However, **barriers** are found:

- Lack of a systematic value-chain integration approach for re-use of composites.
- Poor customer acceptance for remanufactured products.
- Lack of circular business models for boosting profitability.
- Unstable and unpredictable EoL products flows.

Motivation for a cross-sectorial approach

Leveraging on a cross-sectorial approach can open new potentials for composite made parts recycling, remanufacturing and re-use under a systemic circular economy perspective.





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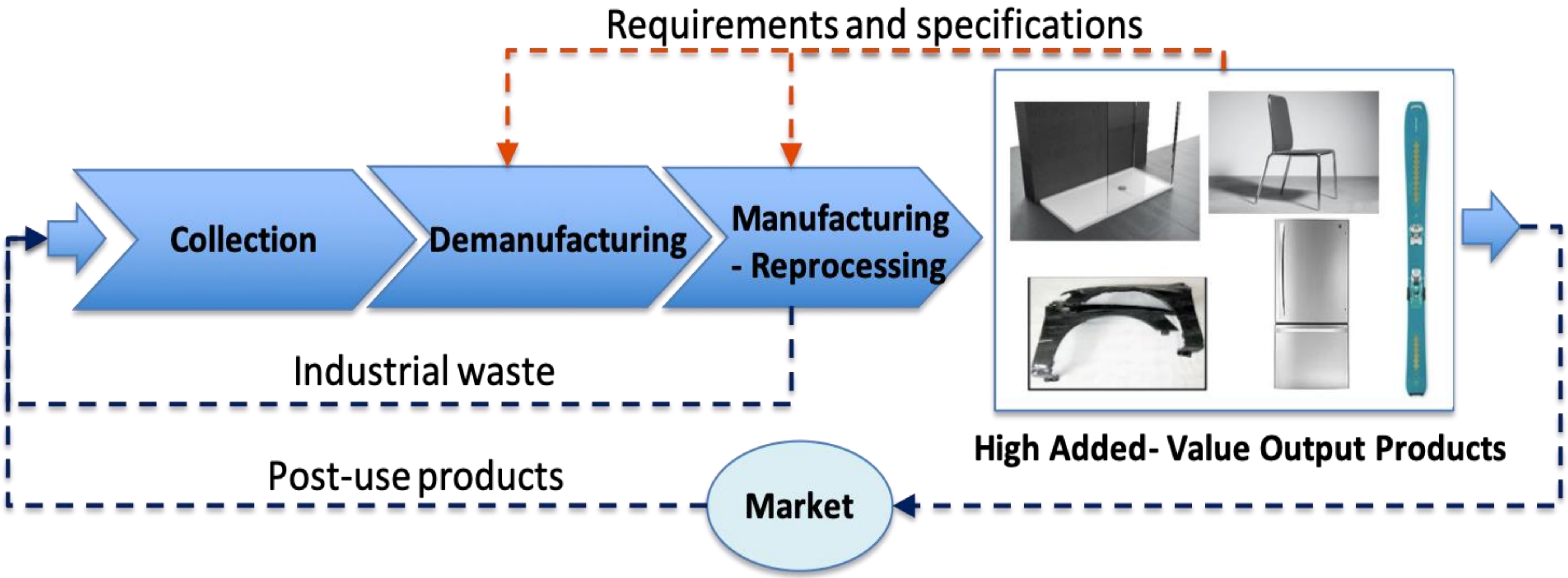
The demand-driven approach



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Recycling of composites

Recycling

Mechanical

- Relative good quality
- Low energy consumption
- Loss of material properties

Thermal

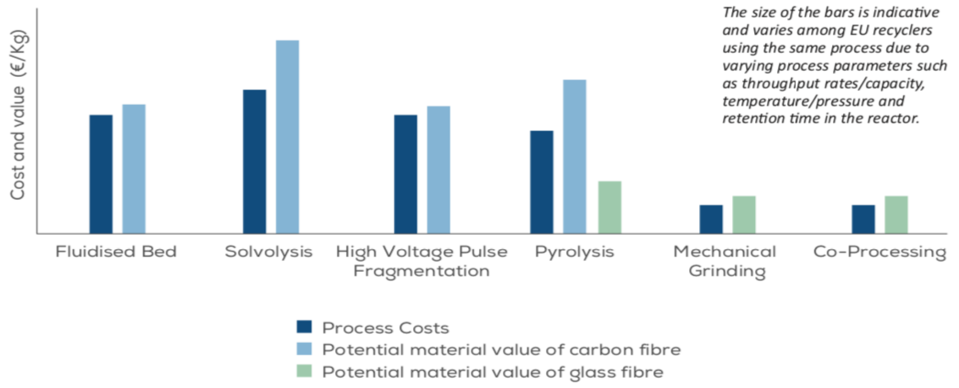
- Good output quality
- Energy intensive
- Waste water
- Air pollution
- Possible degradation

Chemical

- Good output quality
- High costs for solvents
- Waste water
- Possible degradation

High Voltage Fragmentation (HVF)

FIGURE 9
Estimated relative costs and values of composite recycling technologies



Source: Bax & Company and ETIPWind

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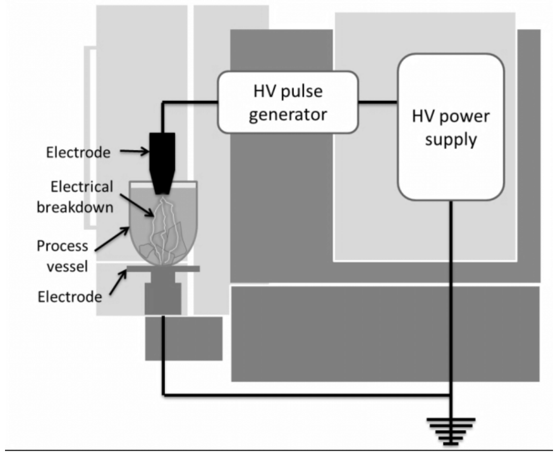
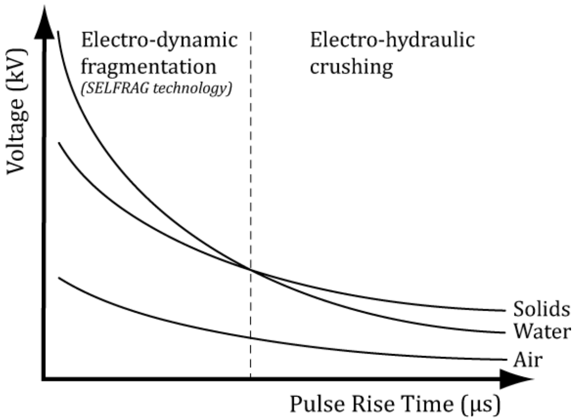
High-Voltage Fragmentation





- Dielectric ambient (de-ionized water, non-conductive samples)
- Creation of a strong, fast growing voltage (80-200 kV, <500 ns)
- Consequence of voltage, high electric field: dielectric breakdown
- Spark plasma channel: diam. 10-50 µm, 10^9-10^{10} Pa, 10^4 K
- Tens of kbar shockwave within a 3 mm diameter from the spark channel
- 250 – 1000 discharge cycles to disintegrate the sample

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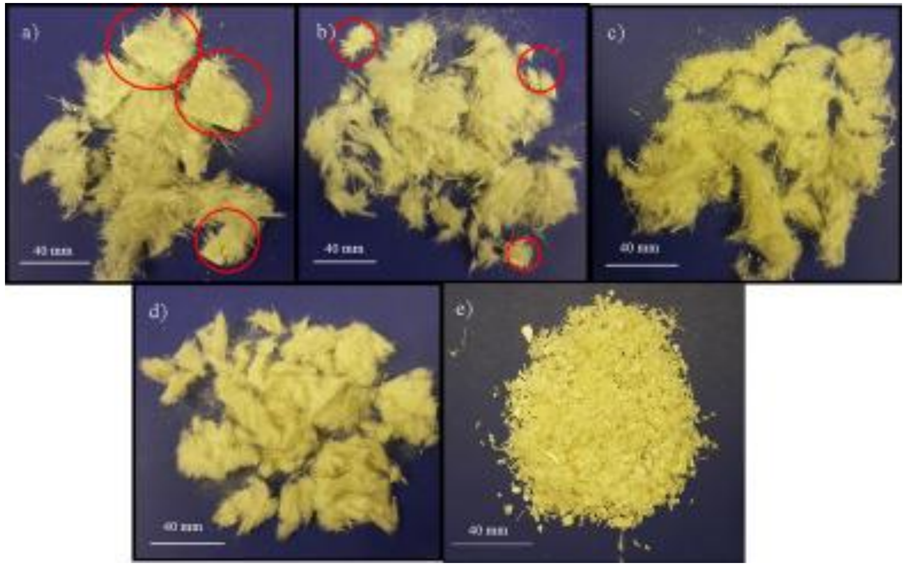
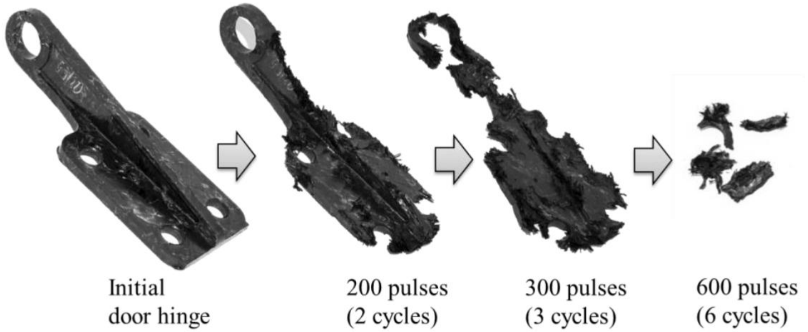
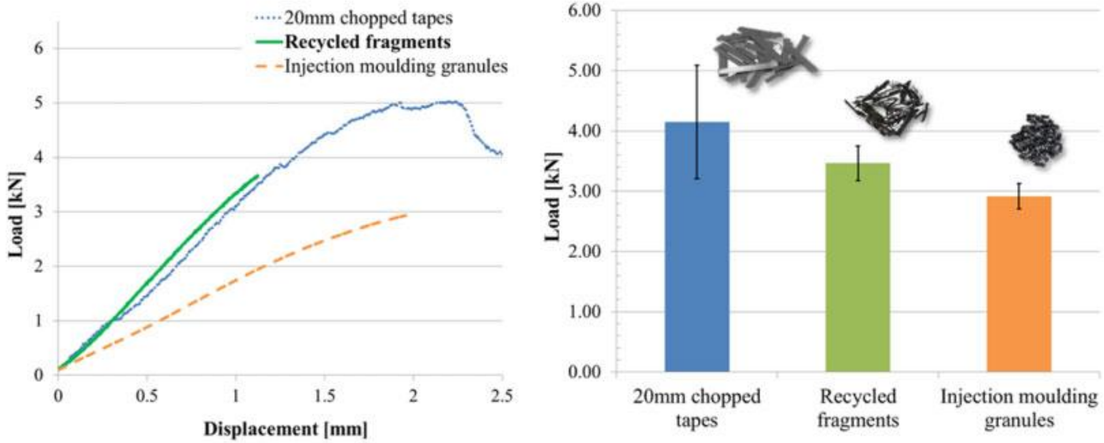
Examples in literature

Studies clearly highlights the **potential advantages** of using HVF over mechanical methods for the recycling of GFRP composite waste.







The HVF technology has been tested on **PEEK-CFRP** hinges used in the aerospace sector. Tensile tests made on hinges made by 100% recycled material show good mechanical properties.

Mativenga, P. T., Shuaib, N. A., Howarth, J., Pestalozzi, F., & Woidasky, J. (2016). High voltage fragmentation and mechanical recycling of glass fibre thermoset composite. CIRP annals, 65(1), 45-48.

Maxime Roux et al. Thermoplastic carbon fibre-reinforced polymer recycling with electrodynamical fragmentation: From cradle to cradle. Journal of Thermoplastic Composite Materials, 30(3):381–403, 2017.

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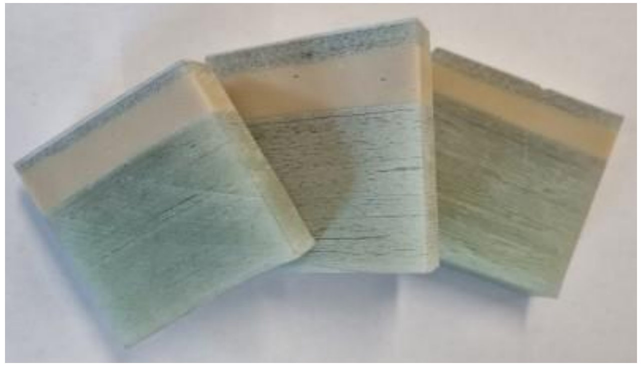
Materials and methods



Design parameters

- Volume of the vessel
- Material of the electrodes

Controllable parameters

- Voltage (90-200 kV)
- Distance between the electrodes (10-40 mm)
- Frequency of the discharges (1-5 Hz)
- Number of discharges
- Presence and dimension of the discharge grid

Analysis

- SEM
- EDS
- Dimensional distribution
- Energy consumption (preliminary)

Factor	Levels
Grid size (mm)	0, 1, 2, 4
Voltage (kV)	150, 180, 200
Number of pulses	Up to 2000
Frequency	5
Distance (mm)	15

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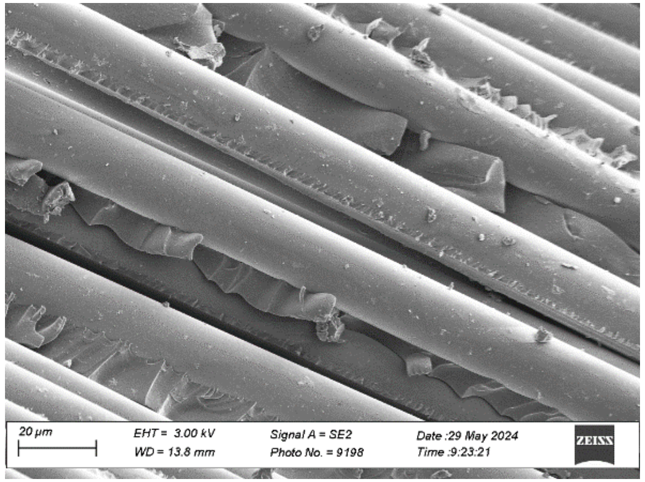
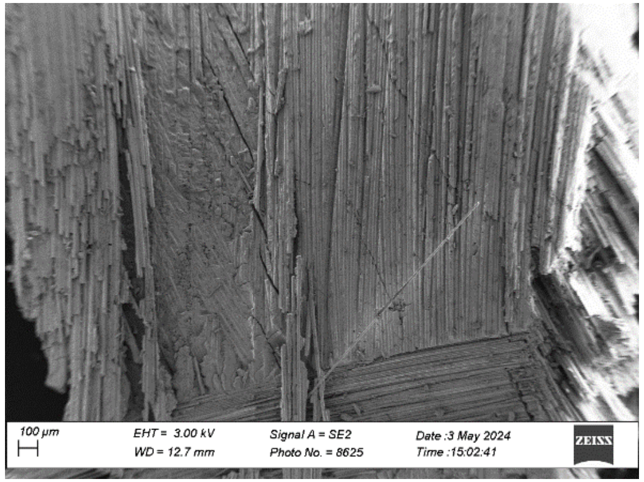
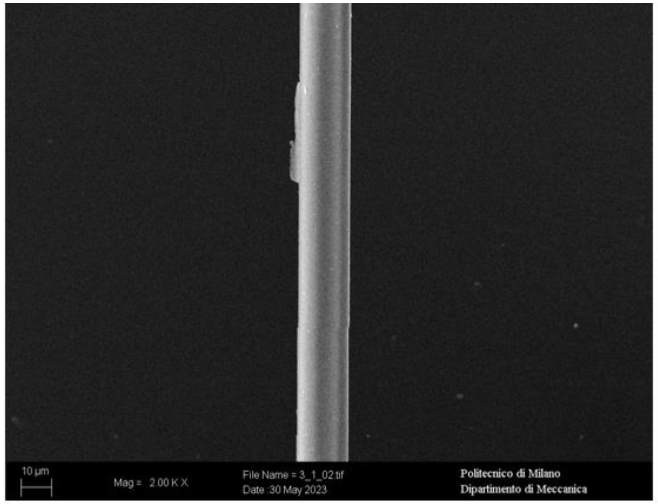
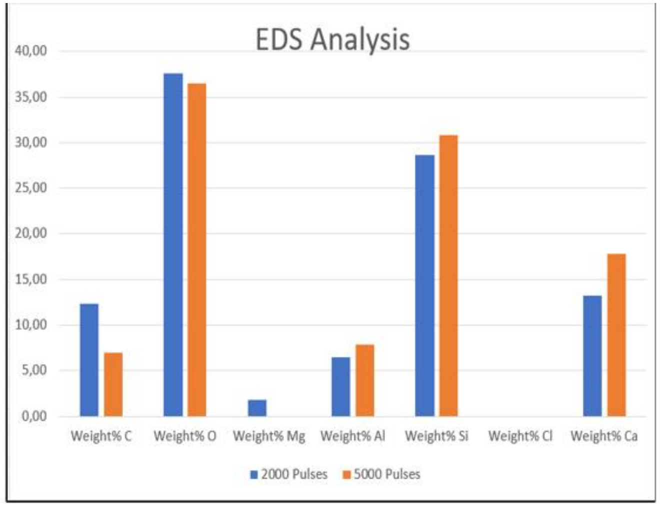
Results: SEM and EDS – EoL Wind blades









- From the analyses, the obtained material can be divided into ***two classes*** of recyclates.
- The first group consists of fibers that are ***mechanically weakened*** but not fully liberated, yet relatively clean, as observed in figure the on the left.
- The second group comprises singular, ***clean, and fully liberated fibers*** with minimal resin content, it was observed that these were found in the lower fractions of the sieve.
- Spectroscopy analysis on the fibers, as shown on the left support these findings.
- Carbon content, used as an indicator of resin residue, was found to be around ***10% after 2000 pulses***, with the remaining composition primarily consisting of oxides of silicon, aluminum, and calcium, ***characteristic*** of e-glass fibers, the most common type of fiber reinforcement used in wind turbines.

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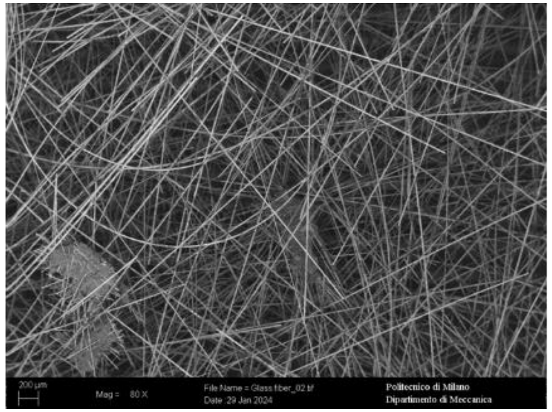
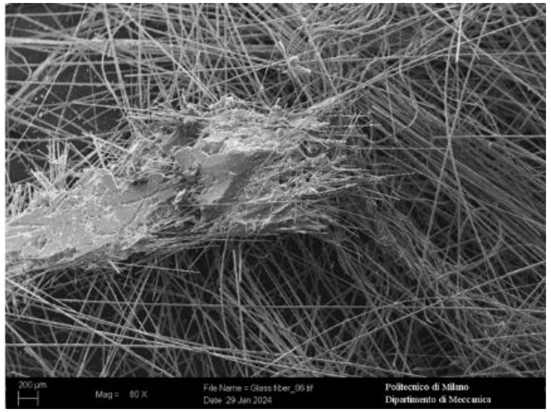
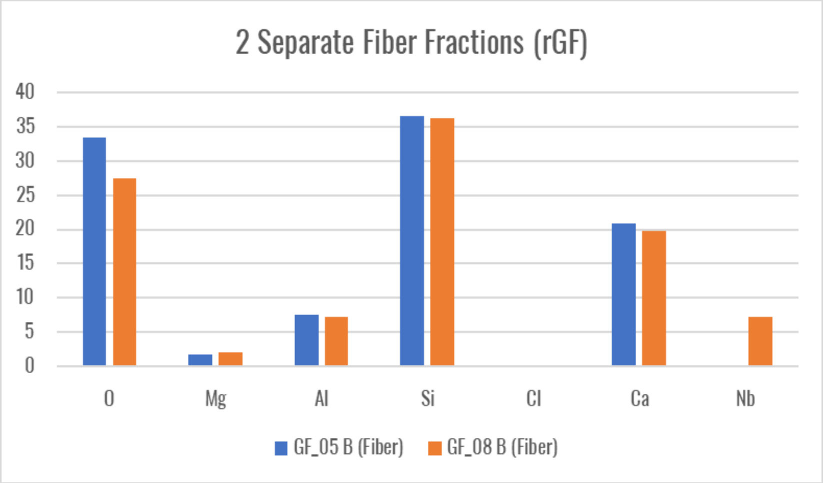
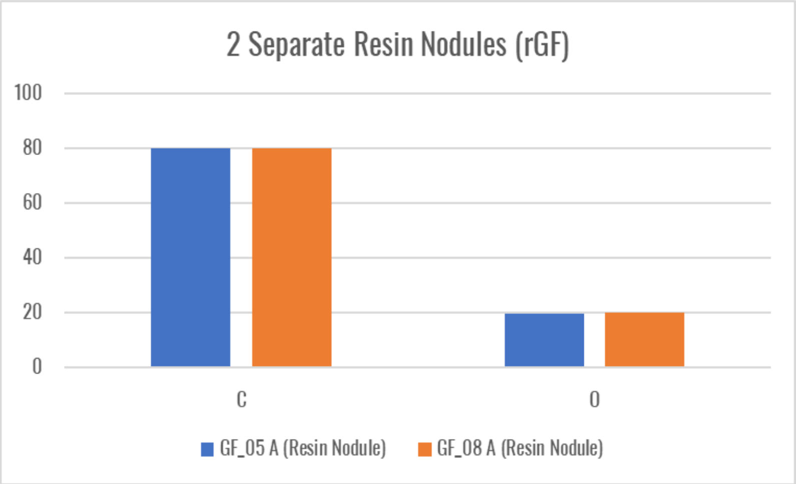
Results: SEM and EDS – Ski Prepregs









- From SEM images, the fibers appear clean and relatively liberated, with the analysis conducted on a ***random, non-selective sample*** indicating homogeneity.
- At the same time, there is a distinct presence of resin nodules.
- As previously observed in ***SEM imaging***, the fibers are confirmed to be clean.
- The composition primarily includes oxides of magnesium, aluminum, silicon, and calcium, which is typical for glass fibers, along with resin nodules rich in carbon.
- An impurity of niobium was detected, likely resulting from other tests conducted in the SEM machine.

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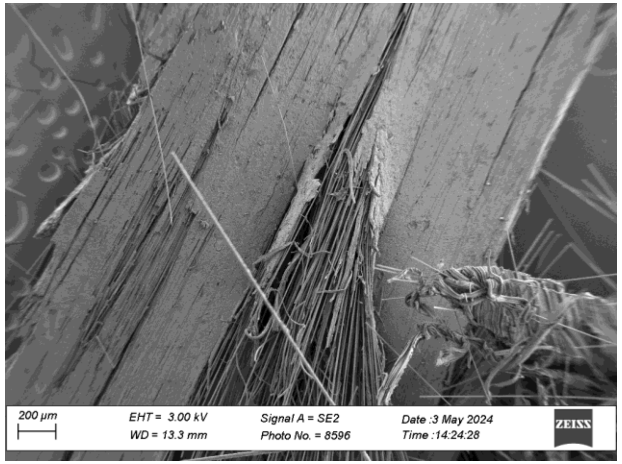
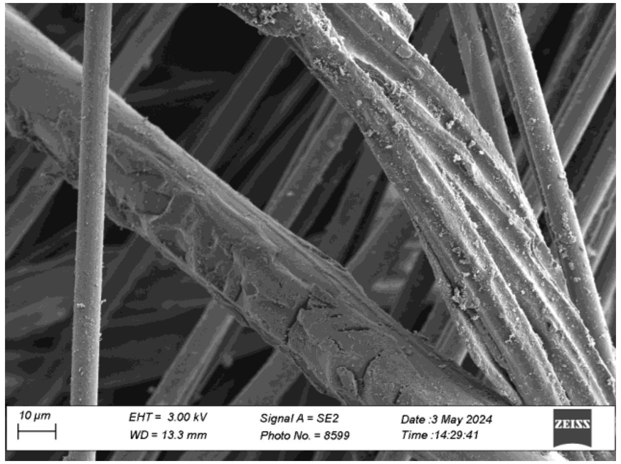
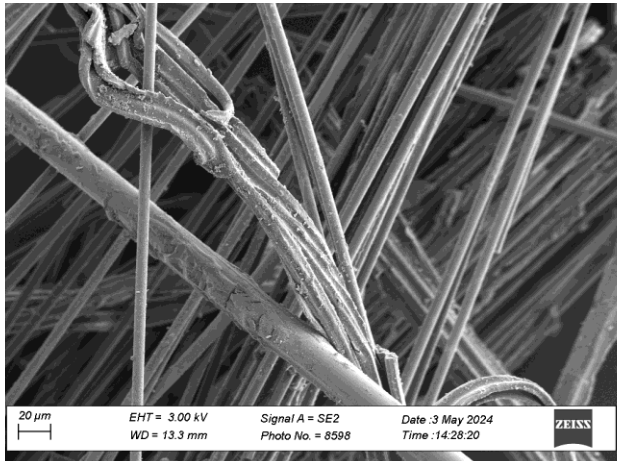
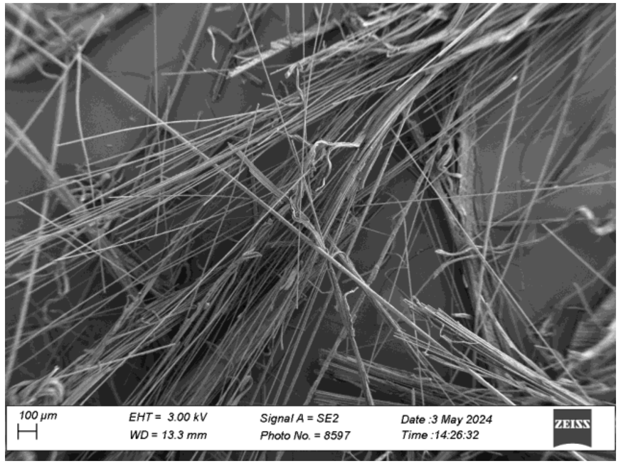
Results: SEM and EDS – Tennis rackets









- The fibers remain largely grouped, with only a few fully liberated.
- A significant ***complication*** arose during the treatment of these pieces. The black color of the material caused the water in the system to turn black, which in turn triggered the water sensors to halt the process, ***disrupting*** the operation of the machine.
- This issue has to be solved if there is the interest to use this machine with this kind of materials. As the non-liberated material, the EDS analysis have not been conducted.

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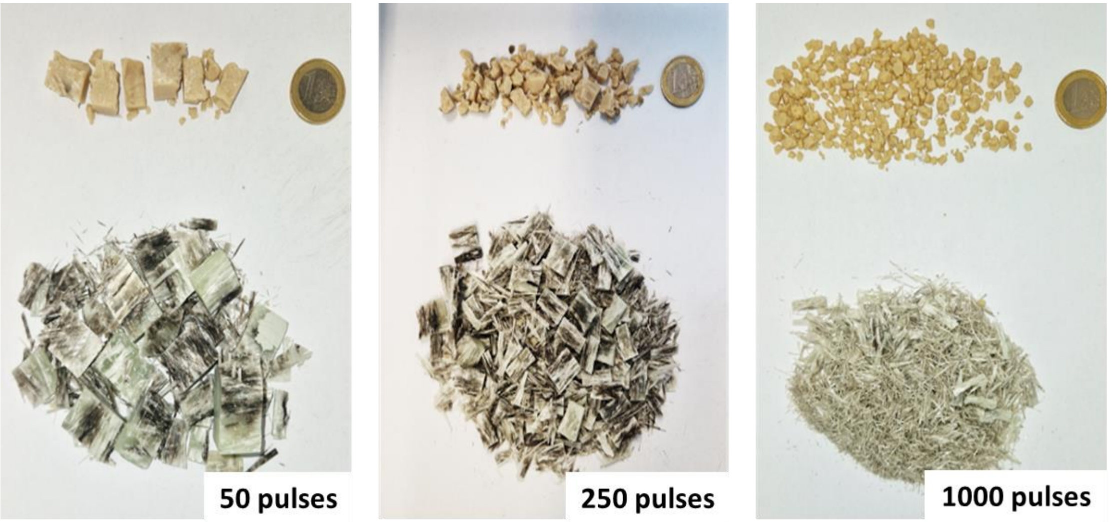
Results: Separation of impurities



- The machine works on the principle of **selective fragmentation**, which exploits the **difference in electric permittivity** of different materials (as PU from fiber-matrix).
- HVF can be used to **liberate** the target material from **impurities** (as PU, balsa wood, ...), **facilitating their separation** with traditional recycling technologies (e.g., optical separation).
- However, with an **increasing number of pulses** the **size** of the PU **reduces** (mainly due to shockwave side effect that propagates in the medium), **increasing** the **energy consumption** and making its separation more **complex**.

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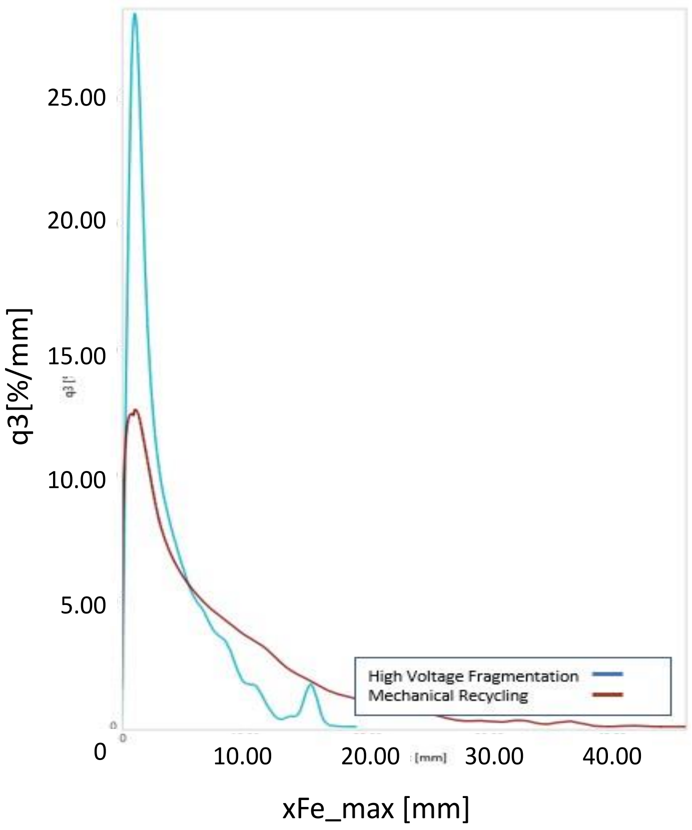
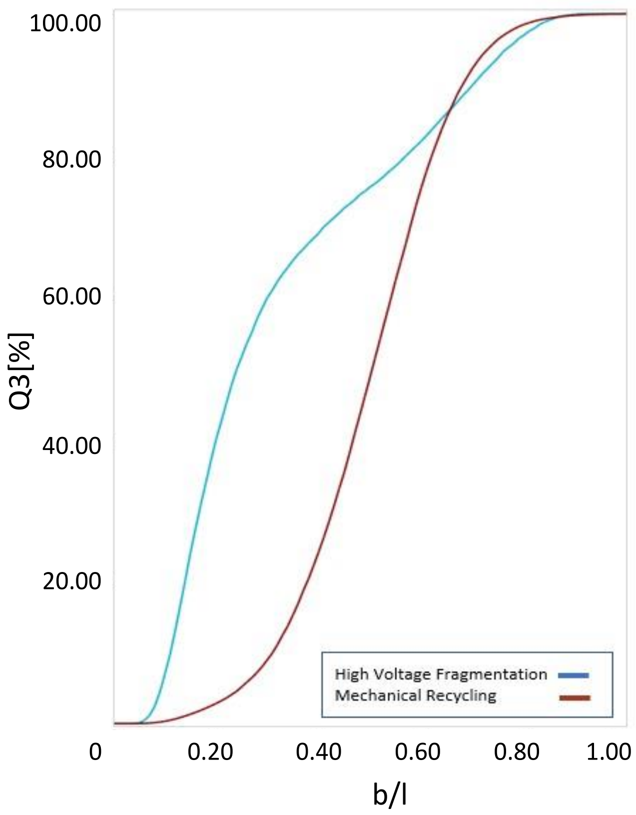
HVF vs Mechanical recycling





- The material obtained with **HVF** with the sieve inlay was compared with the one obtained through **shredding** with a cutting mill in using a 1 mm grid.
- The material processed with **HVF is narrower** around 1 mm, while the fibers mechanically recycled had a wider spread in terms of length.
- Considering the aspect ratio of the two samples, **HVF** seems to be able to obtain **more elongated particles**.
- The material obtained with **shredding** has a considerable quantity of **powder** material, opposite with the one obtained with HVF, due to the physics behind the mechanical process.
- Also in this case, these results are not good or bad in an absolute way, as the **shape** of the material is an important factor for the **demand-driven** approach.

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Conclusions and future perspectives

What can we conclude?

- In this work, **HVF** technology has been applied to recycle **EoL wind blades, Ski prepregs & Tennis rackets**
- From SEM and EDS analysis, HVF shows an **intermediate behaviour** between traditional **mechanical** and **thermal** recycling while clean fibers can be obtained
- Higher amount of these **clean fibers** are seen in the material obtained from **ski's prepreg**, with a low content of resin nodules, while problems arose with CF due to the black color
- The technology, however, seems to work with **multiple types of composites**, both cured and uncured, opening reprocessing possibilities in high-added value products.
- HVF results to be an effective technology to **liberate impurities**, facilitating recycling and reuse of composites in high-added value products

What are the next steps?

- A **full-factorial experimental plan** is needed to understand the influence of the different process parameters and to find the **optimal ones**
- The monitoring of the **energy consumption** is fundamental at this point, together with the **wear of the consumables**
- The development of a **physics-based model** is ongoing

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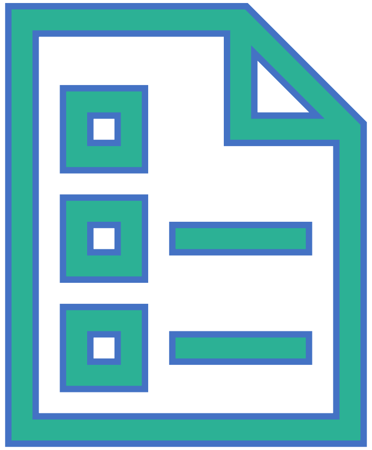
Questions?



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Thank you for your attention!

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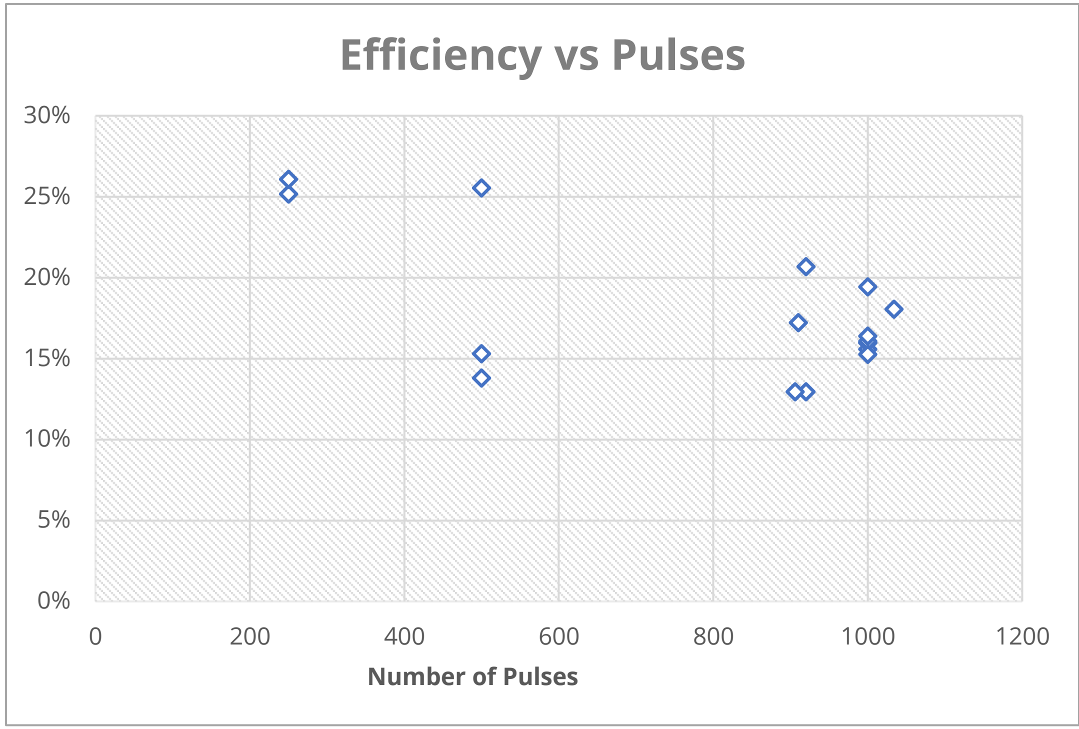
RE Energy Assessment - Electrofragmentation

S.no	M_{in} (g)	Gap (mm)	Pulses	Energy converted (J)	Energy consumed (J)	Energy Consumed(kWh)	Efficiency
1	16	15	1000	1,15E+05	7,20E+05	0,2	16%
2	16	15	1000	1,12E+05	7,20E+05	0,2	16%
3	16	15	1000	1,15E+05	7,20E+05	0,2	16%
4	16	15	1034	1,30E+05	7,20E+05	0,2	18%
5	16	15	1000	1,16E+05	7,20E+05	0,2	16%
6	16	15	1000	1,10E+05	7,20E+05	0,2	15%
7	16	15	1000	1,18E+05	7,20E+05	0,2	16%
8	30	25	1000	1,40E+05	7,20E+05	0,2	19%
9	30	30	920	1,40E+05	1,08E+06	0,3	13%
10	20	30	906	1,40E+05	1,08E+06	0,3	13%
11	16	30	910	1,55E+05	9,00E+05	0,25	17%
12	16	30	920	1,49E+05	7,20E+05	0,2	21%
13	16	30	500	8,69E+04	6,30E+05	0,175	14%
14	20	30	500	8,26E+04	5,40E+05	0,15	15%
15	30	30	250	4,53E+04	1,80E+05	0,05	25%
16	30	30	250	4,70E+04	1,80E+05	0,05	26%
17	30	30	500	9,20E+04	3,60E+05	0,1	26%



- Measurement has been carried out using a Schell Easy Count 3 – current meter
- HVF has a standby consumption of 0,1 kWh
- Energy efficiency is seen to be less dependent on mass processed or electrode gap but more on the number of pulses.
- Primary evaluations show that higher efficiency is recorded with lower pulses.
- 500 pulses seems to be the optimal choice.

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