Final Report Summary - SELFRAG CFRP (High Voltage Pulse Fragmentation Technology to recycle fibre-reinforced composites)

Executive Summary:
The usage of Carbon Fiber Reinforced Polymer (CFRP) composites in aerospace engineering has increased considerably in last decades because of their efficient and lightweight structure for better airplane performance. This represents a challenge to the aviation industry. As no real recycling strategy in economic rages is available, no efficient end-of-life solutions for airplanes exist. Current mechanical combined with chemical processes target to remove the resin matrix from the carbon fibers by thermal degradation. Problematic is the low quality product recovery of carbon powder with little to no economic value. Other solutions like incineration and landfilling results in the complete loss of the material. The current downcycling of CFRP material is critical. New methods are being developed in order to increase
Within the Clean Sky project JTI-CS-2012-1-ECO-01-053 - Disintegration of fiber-reinforced composites by electrodynamic fragmentation technique - SELFRAG investigates the potential of electrodynamic fragmentation to improve the recyclability of CFRP waste from end-of-life aircraft components. SELFRAG proposed a detailed test plan; the work is broken down into 3 main work packages. Each work package is subdivided into several tasks, which provides milestones and deliverables. The principle of electrodynamic fragmentation provides a selective physical process using high voltage pulse power discharges to liberate composite materials along material interfaces. The main objectives of the project are the process development to treat CFRP composites for best fiber recovery and to install a demonstrating plant in TRL 6. This includes investigations to the recyclability of resulting products and the potential recycling rate. Lab scale tests indicated a recycling quote of 60% by the removal of polymer and losses. Tests to thermoplastic PEEK material showed the recycling potential of the process by the complete reuse of the processed material in new parts with comparable material strength. In the process development best electrodynamic plant setup and process conditions are developed in regards of energy consumption, scale and fiber recovery in lab scale tests first. To construct and setup the demonstrator the data was converted to upscale specification of the potential demonstrator. For the construction of the demonstrating plant the data was integrated in the equipment and flow-sheet design including electrodynamic fragmentation and material recovery devices. To treat CFRP material two general setup of the demonstrating plant were considered. Plant E was setup to treat CFRP <60 mm in size. Plant D setup was chosen to treat larger components. After the construction and installation of the demonstrating circuits, plant performance was successfully demonstrated. Both plants were evaluated, but only plant E setup included a competitive treatment of CFRP composite for recycling. Nevertheless it was demonstrated that also large CFRP components can be treated by SELFRAG. The best demonstrator setup achieved a throughput of 5.65 kg/h using 1.2 kWh/kg at best process conditions. The economic evaluation of the demonstrator circuit is near to be economic. To improve the economic figures require an increase of the pulse repetition rate and material throughput. Projections using higher pulse repetition rates influence the economics of the plant considerable with a potential 3 year return of investment and yearly production of 84 tpa of a single generator equipment. The successful demonstration of electrodynamic fragmentation in TRL 6 provides a solution to treat CFRP material from end-of-life airplanes. The economics indicate a profitable application at industrial scales to close material cycles in recycling for the aerospace industry.

Project Context and Objectives:
Carbon-fiber-reinforced-polymers (CFRP) have known advantages and are widely used in different industries from aerospace, automotive to leisure. In past decades the usage of CFRP composites in aerospace engineering increased considerable. The lightweight structure and high material strength provides a robust and still light material to design airplanes with better performance and reduced fuel consumption – an important step to keep costs reasonable as energy prices increased over proportional in the past few years.

Today aeronautical industry has no real end-of-life solutions for the different CFRP composites from airplanes. As increasing amounts of CFRP composites are expected from end-of-life airplanes new process to treat these waste streams are urgently needed. Existing mechanical combined with chemical processes results in downcycling with low quality carbon fiber recovery. Incineration and landfilling are still
widely used but are the wrong way for the highly valuable material. A more efficient method is being explored by SELFRAG under the umbrella of the aeronautical research program Clean Sky with the project JTI-CS-2012-1-ECO-01-053 – “Disintegration of fiber-reinforced composites by electrodynamic fragmentation technique”. The method is based on the interaction of an electrical discharge with a solid between two electrodes immersed in water. The process can be separated in different phases and causes a highly selective fragmentation along material interfaces. Figure 1 explains the principle of HV pulse power fragmentation principle. The reduction of the pulse rise time to < 500ns changes the electrical behavior of materials. In such a setting the breakdown voltage of water increases and is larger as for solids. This makes it more likely that the discharge occur towards and into the solid for processing. Figure 2 explains the physical principle more detailed. The reduced pulse rise time affect the polarization mechanisms of mainly water. As a dipole water molecules are too slow to rearrange in the evolving electrical field. Molecules in a solid on the other hand have no space to maneuver, but do have a small amount of free electrons “floating” about in their structure. These electrons quickly get accelerated, knocking other electrons out of place, starting an avalanche effect that ultimately causes the electrical breakdown. This electrical breakdown channel or plasma arc is very similar to lightning, causing a strong shockwave by the sudden collapse of the plasma arc which will ultimately fragment solid. As the free electrodes are situated and transported to material boundaries the discharge and fragmentation energy is placed along material interfaces which results in the highly selective fragmentation of the products. This allows an intact recovery of the components. SELFRAG tests to different materials have shown that the principles operate for various inorganic materials from mining to recycling. The treatment of CFRP composites by electrodynamic fragmentation has therefore a high potential to improve carbon fiber recovery by the selective fragmentation of airplane end-of-life CFRP.

The overall objective of the project is the implementation of a specific electrodynamic fragmentation plant to process CFRP’s with the goal to regain non-damaged carbon fibers for a real recycling of end-of-life CFRP composites from airplanes. SELFRAG is a manufacturer and expert of electrodynamic fragmentation equipment and has the project objective to develop the demonstrator within the Clean Sky initiative. This final report summarizes the overall project achievements and milestones. The different steps within the project have the objectives to investigate carbon fibers liberation using electrodynamic fragmentation in laboratory scale. Further objective is to test the recyclability of the liberated fibers. SELFRAG partners evaluated the treated products and investigated the introduction of recycled fibers into new CFRP products. In regards of processing the objective is to evaluate the electrodynamic process performance. This is part of the process development for CFRP treatment from laboratory scale to demonstrator level in TRL 6. The objective includes the development of evaluation criteria for processing, development of upscale specifications, construction and demonstration of the continuous operating demonstrator as well as the evaluation of demonstrator performance in regards of capacity, energy consumption and economic potential.

The work to develop the demonstrating plant is broken down into three work packages (WP). The first two WP concerns the process development in lab scale followed by the upscale and construction of the demonstrator in the final WP. The objective in WP 1 is to evaluate the influence of all electrodynamic process variables to selected samples of various CFRP composites: thermoset, thermoplasts and fiber-metal laminates. The objective of WP 2 concerned the optimization procedure on lab scale to improve CFRP liberation at relevant energy levels and provision of plant specifications for the upscale. The recyclability of treated carbon fiber is done to evaluate the recycling potential of the process products. The objective of WP 3 is the construction, installation and evaluation of the continuous operating SELFRAG.
demonstrating plant in TRL 6.

The ultimate goal of the project is to demonstrate the recovery non-damaged carbon fibers by the liberation of carbon-fibers from end-of-life CFRP composites using the electrodynamic principle. The objective is to develop an electrodynamic fragmentation plant to demonstrate the technology in a TRL 6. The project has a large potential to provide aviation industry a real recycling process to close material cycles for the high valuable carbon fiber material.

Project Results:

1. Sample setup
To prepare the tests the first step was the selection of suitable test material. Maxime Roux from FHNW, Switzerland, provided thermoset and thermoplast PEEK material in different configuration and quantities. As basic requirement for the WP 1&2 the samples were cut into suitable and similar sizes of 40 mm x 40 mm to fit into the process area. To process material during demonstration in WP 3 shredded end-of-live material was delivered from Fraunhofer IBP in a size < 60 mm. To test larger sizes SELFRAG organized large thermoset parts to process. Figure 3 displays different used material in the project and Table 1 summarizes general features of the samples used in WP 1 & 2.

The samples of thermosets includes RTM6 / NCF 7μm HTS40 and RTM6 / NCF 5μm. Treated thermoplasts are PEEK/CF UD (uni-directional). The thermoplast material is composed of a PEEK thermoplastic matrix and of carbon fibers as reinforcement. The PEEK polymer is manufactured by VITREX under the trade name of PEEK 150PF and PEEK 450XF with a processing temperature between 380 and 400°C and a density of 1.3 g/cm³. The reinforcement is high performance carbon fibers with 5 μm diameter manufactured by HEXCEL (AS4 and IM7) with a density around 1.79 g/cm³. The composite material is processed by SUPREM. The carbon fiber bands are impregnated with PEEK powder to produce composites tapes. For the initial tests of WP 1 UD, only tapes are used.

2. Equipment
To determine the basic process conditions of an electrodynamic fragmentation device, the call for projects (JTI-CS-2012-01-ECO-01-053) specified a lab-scale plant with the following specifications:
- High voltage cascade generator with adjustable voltage range between 90-200 kV,
- Variable pulse frequency 1-5 Hz,
- Movable electrodes,
- Variable electrode configuration,
- Automated electrical grounding,
- Tool for monitoring electrical parameter.
The cascade generator is based on the concept of a Marx generator to produce short termed discharges suitable for electrodynamic fragmentation. The setup of the lab equipment was maintained during WP 1 and 2.

3. Test design
For WP 1 and 2 dedicated test programs in factorial design of experiment were elaborated and agreed with project partners. In WP 1 the influence of equipment setup and different process parameter to the different CFRP composites were investigated. Process variables tested were voltage, total energy input, electrode gap, electrode size and its effect to different materials. To have a close control of the process-material interaction a single particles assessment was installed. Each test was interrupted in defined energy increments in an open circuit design. The achieved size reduction was monitored by the remaining oversize. This provided a basic understanding of material behavior in the fragmentation process. In WP 2
further process variables like filling grade, particle orientation, residence time process strategy were compared for the different CFRP materials. The data from both WP were used to develop plant specifications for the upscale.

In WP 3 the demonstrating plant was constructed and installed. In the evaluation of the plant performance it was tried to evaluate best processing conditions to guarantee fiber liberation. Target was to achieve sufficient liberation without overprocessing of the CFRP feed. Two different plant setups were elaborated after WP 2. Both setup were tested and compared. The process variables for the optimization loops were according the selected setup and concerned mainly the specific energy introduction.

4. Process development of WP1&2
In WP 1 the progress towards the objective to evaluate process parameter and equipment settings for different CFRP was initiated by the selection of suitable samples using three different CFRP composites: thermosets, thermoplast UD PEEK and thermoplast chopped tapes PEEK. To exclude artifacts from sample heterogeneities and to get comparable results from all different material similar sizes, volumes and shape were prepared. Fiber-metal laminates were not included as project partners could not provide them for the tests. After the setup of the test equipment the further progress towards the WP 1 objective was achieved by the development of a test plan in factorial design of experiment. The data analysis after execution of the test plan discriminated main process variables. An elaborated test plan of 16 tests per material was performed. Within that a single particle assessment was selected including a very low filling grade of the vessel to keep conditions comparable and to avoid artifacts from the material. To get an understanding of the influence of the process to the material each test was done according a developed strategy including a treatment in defined energy increments. The achieved fiber liberation was monitored by the remaining oversize. As a result of the work progress a better understanding of the material behavior in the SELFFRAG process was achieved. The developed evaluation tool to interpret the data allowed the discrimination of process conditions and equipment setup. At the end of WP 1 the objectives of the WP were successfully achieved and basic process conditions and equipment setting for the following WP provided. The used treatment procedure gave an in-depth understanding of the material-process interaction in steps.

During WP 1 the general behavior of the material in the electrodynamic fragmentation process was described. The energy introduction needs to overcome a barrier before size reduction occurs. In this initial step no active fragmentation is visible but a swelling and opening of the texture occurs. The opening of the structure provides new pathways for the process to enter and trigger a fast and sudden size reduction to final liberation. The described size reductions were different at different conditions (Figure 5) and were used to define best conditions.

Figure 6 presents some pictures of different treated thermoset material and demonstrate the results using different process variables but a comparable total energy input. As result of WP 1 the best size reduction and fiber liberation were achieved at high voltage, low electrode gap above the feed and larger electrode sizes. The progress towards the objective were finalized and achieved. All required milestones were successfully reached. The discriminated conditions defined the setup of the HV generator and the basic process parameter. The single particle tests in WP 1 showed a large variation of the data ranging largely with values up to >12 kWh/kg. In best configuration of the selected process variable a specific energy of 4.5 kWh/kg was reached. The processing data was comparable for the different used CFRP composite. Still very different size reduction and liberation pattern were observed. This mainly depends on the texture of the material. After the initial opening of the structure more complex structures are liberated from the outside. Corners are removed first and more rounded particles occurred towards intense treatment.
In WP 2 the progress towards the objective to optimize fiber liberation processing started with the selection of new samples. As for WP 1 similar size, shapes and volumes were prepared. The work progressed by applying the developed conditions and comparing process variables relevant for continuous application. For that a test program in factorial design of experiment with dedicated tests to open and closed circuit designs, filling grades, residence times, and orientation of the feed as well as the occurring circulating load was prepared. Resulting products were evaluated in regards of separation from the process and recyclability. The dedicated test program was realized and the data evaluation showed that processing was further improved to 2 kWh/kg specific energy mainly by the filling grade. Open and closed circuit tests showed similar results and a potential throughputs of 1.2 kg/h was achieved by the used setup (Figure 7).

Mainly thermoplast PEEK material behaved similar. Thermosets indicated a different behavior. Based on their different setup and texture as thermoplast the full fiber liberation reacts not that significant to different filling grades. The simulations of continuous application in lab were comparable to open, batch results and confirmed the achievements from batch tests. Stable conditions were reached at different residence times and circulating loads. Closed circuit design showed an improvement and required less specific energy at comparable filling grades. The progress in the project achieved in-depth knowledge to fiber liberation and recyclability of products treated at best conditions.

5. Recyclability of Products

The progress towards the objective was further achieved with the investigation to the recyclability of the SELFRAG product. In a first step the effective separation from the process was tested. For thermoplast a classification at 4 mm was suggested by projects partners. The sieving of the samples at 4 and 0.5 mm provided the material to tests or recyclability. First successful tests to a SELFRAG recycled thermoplast chopped tapes door hinge were successful and presented by project partners at the SEICO meeting 2013 in Paris and at Greener Aviation conference 2014 in Bruxelles.

For the study, a lightweight rotorcraft door hinge made of thermoplast PEEK chopped tapes has been developed at the FHNW (Figure 9). The material was deposited in the mold cavity and pressed at high temperature (360 °C) for several minutes. SELFRAG recycled chips were processed using the same parameters as the chopped tapes and injection granules (24 vol% CF - Fiber length below 1 mm). In the original chips supplied by the manufacturer, the fibers were well-embedded in the polymer. On the SELFRAG recycled fragments, most of the fibers were not broken or damaged. After the SELFRAG fragmentation, a lot of polymer has been removed from surface of the fibers; some fibers are entirely free of polymer. Figure 10 show an SEM comparison of new and recycled thermoplast PEEK.

Mechanical tests on the different produced door hinges showed comparable results (Figure 11). The door hinge made of recycled chips exhibits a slow plastic deformation and better results than the one made of injection molding material granules. The recycled door hinge achieved 83% strength of to the new manufactured hinge with chopped tapes. The overall strength of the recycle hinge provides very interesting material properties. In the tests a recycling rate of >60% from the initial mass was achieved.

The remaining masses are fines, losses by dissolved material and oversize. The test confirms that a combination of manufacturing and recycling techniques has a high potential to close the cradle to cradle loop for thermoplastic composites for the aerospace industry.

Fraunhofer investigated the fiber liberation of thermosets and presented the results at Greener Aviation conference 2014 in Brussels. The evaluation indicated clean and undamaged carbon fiber with little or no epoxy attachments (Figure 12). Maxime Roux from FHNW provided micrographs from thermosets composites treated and liberated by electrodynamic fragmentation (Figure 13). The thermoset used the
epoxy RTM6 with a reinforcement NCF fabric. The good liberation of carbon fibers composites indicates the recyclability of thermoset by electrodynamic fragmentation. Detailed Tests to the recyclability to thermosets are pending. Fiber liberation and epoxy attachment seems to be in an acceptable range. Fiber length is based on a distribution according to starting material and indicates the recycling potential for the treated CFRP composites. The interwoven texture of thermosets can results in hairball product similar to pyrolysis. This require further treatment which beyond the scope of the project.

Thermoplast PEEK indicated a real recycling potential with nearly similar behavior of recycled products compared to new produced parts. The fiber liberation in thermosets was documented and indicates a significant recycling potential as fibers are clearly liberated from the polymer. Based on the elaborated process conditions, their influence to the HV generator setup and the developed process strategy the progress of work enabled to develop the specifications of demonstrator, including the setup of the HV-generator, the process flow including material handling and the dewatering of the samples.

The progress toward WP objectives was further achieved by first life cycle data to first projections to specific energy, throughput and water consumption. The specific energy of 2 kWh/kg is a 40% reduction compared to conventional technologies in CFRP recycling. The throughput achieved where stable and best at a circulating load of 250%. At the given parameter 1.2 kg/h can be treated.

6. Development of demonstrator specifications

WP 2 included the development of the demonstrator specifications based on previous WP results. The so far achieved results of the project indicate the successful application of SELFRAG to recycle carbon fibers from various CFRP materials. Within tested lab scale it was successfully demonstrated: (i) very good fiber liberation and (ii) tested product recyclability. Projections to operational costs and potential throughputs indicate an interesting alternative to current discussed processes.

For the process development the demonstrator specification included all plant components. This include following plant components: (i) HV components; (ii) process zone including material handling for feed-in and feed-out systems; (iii) Dewatering/material recovery and (iv) water circuit and treatment. Figure 13 & 14 summarizes the developed flow-sheet.

The main part of the plant is the HV pulse power generator including power supply for electrodynamic fragmentation. For the demonstrator a standard multistage Marx generator with suitable short pulse rise time (-500 ns) is required. The HV components should provide 500 Joules per pulse at 170 kV. According different material setup for thermoplast and thermosets in regards to product treatment and different shape requirements the demonstrator setup was decided to be flexible. Therefore two different plant designs were suggested and built in WP 3. The first setup uses a similar scheme as the lab. It is suitable to treat <60 mm feed. The second was designed to treat larger > 60 mm feed. The figures 13 & 14 present the developed demonstrating plants. Main difference is the orientation of the electrodes and feed-out. In Figure 13 electrodes are set opposite and material processed via an internal screen. A water jet removes the material to an external sieving for dewatering and recovery of the fraction -4 mm. Finer fibers are recovered via a band filter.

Figure 14 presents the solution to treat larger CFRP parts. Here the electrode configuration is set parallel and material is fed out by a counter current flow to the dewatering and recovery tools.

7. Construction, demonstration and evaluation of recycling plant

After the definition of demonstrator specifications the initial WP 3 deliverables presented the successful construction and demonstration of the plant and fulfilled the targeted main milestone of the project. Figure 15 & 16 show some examples of the construction phase. Figure 17 & 18 presents the successful
demonstration of the process.

8. Evaluation of demonstrator
The final task concerns the evaluation of demonstrator performance including cost benefit estimates. Thermoplast PEEK recycling using the HV pulse power process showed very good prospective when crushed to <4 mm in lab scale. Potential recoveries achieved ranged between 60-80%. For the demonstration and process evaluation in continuous application, SELFREG and partners could not get enough material for a meaningful test. The tests to thermosets indicated comparable parameters and conditions for both CFRP materials. Due to this only thermosets CFRP are used for to evaluate demonstrator performance.

To fulfill call requirements 2 different equipment setup were installed and compared. For evaluation the process variable are different for the used process flows. For the setup of Figure 13 it is: (i) filling grade; (ii) feed rate, (iii) targeted size reduction.

In the setup the feed is introduced into the process vessel and material rest in the hot zone until sufficient size reduction is achieved that the material can pass the internal screen. The filling grade above the internal screen is crucial for the process efficiency. Test using 1000 g filling grade were best, as higher filling grades have the potential to block the screen.

Main target of the evaluation was to determine best feed rate. In the tests the initial filling grade was kept constant and various feed rate were compared. The optimum situation was found at 1.56 g/s (Figure 19). In that situation the same amount of material leaves the material as is fed. The evaluated process conditions suggested at given process conditions of 190 kV, 5 Hz and a gap of 40 mm a throughput of 5.65 kg/h at 1.2 kWh/kg.

The setup of Figure 14 was also evaluated in a dedicated test design. The achieved data used 42.2 discharges/cm² to liberate fibers from the CFRP composite. This showed that the SELFREG principle can treat larger forms. In the evaluation the achieved specific energy of the tests were similar to the single particle tests of WP 1 and ranged around 5-6 kWh/kg. This confirms that the tests were done under best conditions and that the filling grade is a considerable process variable. In regards of economics it is not useful to treat such parts with SELFREG as the size reduction to coarse size with shredder is less energy intense.

Cost benefit estimates
From the results of lab and demonstrator following key points of the process are extracted. The plant E setup seems to be most competitive in regards energy consumption compared to other methods. Plant D setup uses much higher energies and is not further investigated in the economic evaluation. For further developments a countercurrent feedout seems to be more effective. First tests to prototype sup for lab scale provide promising results.

For the plant E setup basic parameter are 180 kV, 5 Hz at 40 mm gap. The plant achieves
(i) Throughput of 5.65 kg/h. With a availability of 90% and 2-shift operation the yearly production achieves 21 tpa.
(ii) SELFREG production generators manage up to 20 Hz, which ramps up throughput to 22.56 kg/h. With a similar availability of 90% and 2 shift operation the yearly production would achieve 84 tpa for a single generator equipment.
(iii) Energy introduction of the demonstrator was estimated at 0.5 kWh/kg including oversize. In lab tests higher energy input of 1.9 kWh/kg was needed. In average a 1.2 kWh/kg seems to be acceptable for the application to reach sufficient liberation.
(iv) Water consumption. 2 m³/h water in closed circuit is needed with an estimate of 5% losses mainly by
(v) The potential water treatment would need to recover solids and clean the water from dissolved organic components. This was not evaluated in this project.

Following summary describes the economic calculations.

**Contained value:**
- Estimated potential value of carbon fibers 23.00 €/kg
- 60% recovery of high quality carbon fibers for recycling 13.80 €/kg

**Deminstrator Production plant**

**Capital Expenditure CAPEX**
- SELFRAG plant, bandfilter, sieves, buffer tanks, engineering 1'445'000 € 2'045'000 €

**Operational Expenditure OPEX**
- Equipment wear & consumables (electrodes, etc) 3.11 €/kg 3.11 €/kg
- Equipment maintenance (work, etc) 2.00 €/kg 2.00 €/kg
- Manpower (standard worker at 20€/h) 3.54 €/kg 0.89 €/kg
- Power & Water (water losses energy consumption) 0.12 €/kg 0.12 €/kg

**Total OPEX** 8.78 €/kg 6.12 €/kg

**Deprivation*** 6.83 €/kg 4.84 €/kg

***10 years demonstrator/ 5 years for production plant***

15.61 €/kg 10.96 €/kg

The added value for the application based on demonstrator performance using 5.65 kg/h throughput is limited to 5.02 €/kg. Including deprivation to the OPEX even a 10 year deprivation period require additional 6.83 €/kg which is above the remaining added value.

A SELFRAG production plant using one generator at 20 Hz have a considerable influence to economics by the potential increase of throughput to 22.56 kg/h. This affects mainly the OPEX and CAPEX estimation. The CAPEX is increased to 2'045'000 €. The OPEX is reduced to 6.12 €/kg. Potential return of investment is reached in 3.1 years. A 5 year deprivation provides an added value of still 2.84€/kg.

The cost benefit analysis indicates that the economics are negative for the demonstrator but that the developed plant setup operates close to the economic equilibrium. SELFRAG production plants are capable of processing at higher pulse frequency which has a direct influence to throughput. Current state of the art generators at SELFRAG for production plants achieve up to 20 Hz which improves throughputs by a factor of 4. This changes the economics to be positive with a return of investment within 3 years and yearly potential revenues of 649'684 €. The increased throughput of a potential production plant is able to treat 84 tpa which is a suitable size of occurring waste streams from end of life airplanes and/or production wastes.

**Conclusions**

The increasing usage of CFRP composites in aerospace engineering represents a challenge to the aviation industry to guarantee economic and meaningful end-of-life solution. Currently no real recycling strategy is available existing processes are limited either in fiber liberation and/or provide only alow quality product recovery of carbon powder with little to no economic value. This downcycling of highly valuable CFRP from values >20 €/kg to less than 1€/kg is not economic or ecologic. New methods are being developed in order to increase the quality of the recovered carbon fibers but are limited in liberation, recovery of good quality carbon fibers, throughput, high operating costs and/or insufficient industrial scale.

Within the Clean Sky project - SELFRAG investigates the potential of electrodynamic fragmentation to improve the recyclability of CFRP waste from end-of-life aircraft components. In the herein presented final
The project has shown:
• Electrodynamic fragmentation can treat various CFRP materials at energy levels below 2 kWh/kg
• The treatment of thermoset CFRP indicates good fiber liberation from the polymer. The recycling potential of the liberated fibers is increased at industrial scale.
• The treatment to thermoplastic PEEK CFRP show a direct recycling potential without further treatment required. Rheological tests indicate only a low reduction of material strength with a recycling quote of >60%.
• The project showed the successful process development from lab to demonstrator scale.
• SELFRAG successfully constructed, installed and demonstrated the demonstrator circuit to liberate carbon fibers from CFRP composites in TRL 6
• The project demonstrated that also large CFRP components can be treated by electrodynamic fragmentation.
• The best demonstrator setup achieved a throughput of 5.65 kg/h using 1.2 kWh/kg.
• The economic evaluation of the demonstrator circuit is near to be positive. To improve require an increase of the pulse repetition rate and material throughput.
• Projections for industrial scale equipment points to a potential 3 year return of investment by 650’000 € potential revenue/a 84 tpa throughput of a single generator equipment.

The successful demonstration of electrodynamic fragmentation in TRL 6 scale provides a solution to a real recycling of CFRP material from end-of-life airplanes. The economics indicate a profitable application at industrial scales to close material cycles for the aerospace industry.

Potential Impact:
Carbon fiber composites are widely used in aeronautical industry because of their high strength and low weight. Carbon fibers is an expensive material with an unexplored potential to recycle. Currently no real recycling process exists. Current applied processes only result in downcycling of the fibers in regards of fiber recover and quality. By doing so a high valuable material of >20€/kg value is destroyed to <1€ material. Current usage of incineration and landfill even produce costs.

The increasing usage of CFRP composites in airplanes put manufactures of the aviation industry under pressure. Currently no economic end-of-life solution for CFRP composites from airplanes exists.

Manufacturer are looking for real recycling solutions to close material cycles to reduce the increasing cost pressures. To improve the situation the installation of a real recycling strategy and process to recover carbon fibers from end-of-life airplanes has a huge potential of economic value. The increasing demand for the valuable carbon fiber material from different industry will further increase. Main national and European political directives ask for more energy efficient solutions in transportation. Already today the aviation industry have to face a several 100% increase of energy prices. The demand for more energy-efficient engineering has not only reached aviation industry. Already today companies in automotive have started to use to integrate CFRP composites in their products. This development will further increase costs for carbon fibers as the yearly production cannot ramp-up fast enough. To ensure the availability of carbon fiber to the aviation industry and to provide a sustainable end-of-life solution for airplanes the investigation of new processes in Europe are needed to stay competitive in the international manufacturing aeronautical industry. More than this will the development of recycling processes for the carbon fibers manifest the
competitiveness of the European industry.
The presented study proved: electrodynamic fragmentation can be regarded as a step change in the processing industry for materials that are difficult to treat with conventional methods. The project topic to install a demonstrating plant for recycling CFRP was successfully achieved. The tests indicated that the various CFRP composites were processed by maintaining the high value of the material and reducing the required energy by 40% compared to existing methods. This demonstrates the high potential of the technology for a real CFRP recycling. It contributes to strengthen Europe’s image and geopolitical situation as high tech continent with sustainable development for raw materials required for the highly specialized industry. With the closure of material cycles such for carbon fibers Europe follows more sustainable developments to not only produce more efficient airplanes to maintain the jobs of that industry in Europe– it also creates new potential industry to supply material to the industry by real recycling. Therefor the successful recycling of CFRP in suitable industrial scale provides significant strategically advantages for the European aeronautical industry. The increasing demand for CFRP composites from different industries will increase cost pressure on carbon fibers which can be reduced by recycling. Clean Sky consortium members using recycling not only gain by the reduction of costs from end-of-life solutions. To have a suitable recycling process available that reduces the need of primary material has competitive advantages for Europe’s aeronautical industry.

Beyond the Clean Sky application the project results are able to be expanded to other industries. Today CFRP are widely used in different industries also very different to aviation like automotive or leisure. The increasing demand requires recycling strategies. By the development of recycling solutions Europe can take the leadership in such markets. This provides innovation and creates jobs within Europe. The projects impacts to recycling of CFRP are in line with Europe’s policy for sustainable usage of raw material and energy. Actual used processing methods results in downcycling to a low percentage of the initial value of the carbon fibers. Often the treatments are difficult to scale up and include high energy consumption, wear, chemicals and result in alteration of the fiber. Electrodynamic fragmentation maintains the value of the recycle product with a more energy-efficient treatment without chemicals. Current investigations to the process water are ongoing.

The main advantage is that the technology of electrodynamic fragmentation is able to treat industrial quantities. The scalability of the process is sufficient to treat larger capacities. To reach the next TRL requires only low investment and the economics indicate profitable treatment for recycling. This provides a potential solution that can be realized soon to solve current situation of todays and future end-of –live aircrafts. The further development of electrodynamic fragmentation for the recycling industry will strengthen Europe’s leading position in processing technology. More jobs will be created at SELFRAG, partners and client to manufacture, install, and operate plants. This provides jobs that require qualified and skilled personal typical for manufacturing industry. More than that value can be created in recycling centers. Recycling using electrodynamic fragmentation can operate economic for a real recycling. This reduces Europe’s need to support recycling with investment and coverage.

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