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Controlled Pyrolysis: A Robust Scalable Composite Recycling Technology

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Controlled Pyrolysis: A Robust Scalable Composite Recycling Technology

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List of Acronyms

ACMA	American Composites Manufacturers Association
AGS	Above ground storage or above ground staging
ASR	Automotive shredded residue
ASTM	American Society for Testing and Materials
BMC	Bulk molding compounds
CAPEX	Capital expenditure
CED	Cumulative energy demand
CEFIC	Plastics Europe
CF	Carbon fiber or cash flow
CFRP	Carbon fiber reinforced polymer
CHZ	CHZ Technologies
CI	Capital intensity
CM	Compression molding
CO2e	CO2 equivalent
COE	Cost of energy
CSP	Continental Structural Plastics, a Teijin Group Company
DOE	Department of Energy
EBIDTA	Earnings before interest, taxes, depreciation, and amortization
EBIT	Earnings before interest and taxes
EC	Energy credit
EERE	Office of Energy Efficiency and Renewable Energy
EOL	End-of-life
FP	Finished product
FRP	Fiber reinforced polymer
GE	General Electric
GF	Glass fiber
GFRP	Glass fiber reinforced polymer
GWP	Global wind power
IACMI	Institute for Advanced Composites Manufacturing Innovation
IM	Injection molding
L/I	Landfill and/or incineration
LCA	Life cycle analysis
LCF	Long carbon fiber
LCI	Life cycle inventory
LCP	Long carbon fiber price
MCF	Milled carbon fiber
MCP	Milled carbon fiber price
NE	Net energy
NG	Natural gas

NGO	Non-government organization
NIAT	Net income after taxes
NPV	Net present value
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
P&L	Profit and loss
PA-6	Polyamide-6
PE/VE	Polyethylene/vinylester
PVC	Polyvinyl chloride
RE	Recovered energy
RM	Raw material
ROCC	Return on capital consumed
SG&A	Selling, general, and administrative expenses
SMC	Sheet molding compound
TE	Total energy
TEA	Techno-Economic Analysis
TGA	Thermogravimetric analysis
TPD	Tons per day
TRACI	Tools for Reduction and Assessment of Chemical and other Environmental Impacts
UTK	University of Tennessee - Knoxville
VC	Variable Costs
VOC	Volatile organic compound
WC	Working capital
XIRR	Extended internal rate of return

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1. EXECUTIVE SUMMARY

The reinforced composites industry is facing significant challenges in handling the scrap composite material from automobile manufacturing, the wind turbine industry, and others. The fibers in the material, whether they be carbon, glass, or other materials have commercial value if they can be recovered successfully. Successfully means the fibers are clean with no sizing or other binders and have adequate strength and physical properties that would allow them to be economically reprocessed into valuable product.

The composites recycling project was an industry-collaborative effort to develop a composite recycling technology using controlled pyrolysis. Through the recycling of scrap and end-of-life (EOL) cured composite materials, this pilot study was intended to create a business case by realizing a cost-effective means for recycling EOL and production scrap composite materials, ultimately reducing the volume of composite materials destined for landfill. The project was led by the Institute for Advanced Composites Manufacturing Innovation (IACMI), the American Composites Manufacturers Association (ACMA), Oak Ridge National Laboratory (ORNL), Continental Structural Plastics (CSP) a Teijin Group Company, CHZ Technologies, and A. Schulman with support from Owens Corning, John Deere, General Electric (GE), Ashland LLC, and Plastics Europe (CEFIC).

The team studied and tested CHZ Technologies' controlled pyrolysis system, known as the Thermolyzer^{TM}, which operates on a scalable basis to convert organic polymer materials into a clean synthesis gas and char containing the recoverable carbon and glass fiber reinforcement. The recoverable energy contained in the input polymers creates the synthesis gas that can be used to provide heat to the Thermolyzer^{TM} primary reactor in a sustainable manner. That is, once the Thermolyzer^{TM} is started with a small amount of external natural gas, the synthesis gas that is created from the polymers will continue to operate the burners so long as feedstock is supplied. The reinforcing fiber materials remaining in the solid phase char were separated and cleaned for re-use in other polymer systems based on the retained properties of the fibers.

The study created reports (attached in the appendix) on the Mass and Energy Balances, syngas analytics, VOC assessment, yield analysis and other analytics necessary for a Techno-Economic Analysis (TEA) to quantify the economic impact of the recovery and sustainable re-use of the carbon and glass fibers.

The process consisted of 4 steps:

1. Selection of 4 samples of cured composite waste materials from project partners interested in materials recycling and recovering the reinforcing fibers for best case re-use. The materials included glass fiber (GF) polyester/vinyl ester automotive SMC from CSP, GF epoxy balsa/PVC foam wind blades from GE, carbon fiber (CF) epoxy wind blade laminated spar caps from GE, and GF/CF epoxy hybrid assembly from John Deere.
2. Processing the waste composite samples into 1-2" shreds. Packaging the shredded composites into bulk sacks on international shipping pallets for shipment to KUG in Forst (Lausitz), Germany.
3. Pyrolysis of the shredded composites under controlled conditions designed for each polymer system. Collecting samples of the gas and char for analysis.

4. Shipping the char containing the CF/GF back to the US for the next steps of testing the fibers and developing protocols for sustainable re-use of the fibers in composite applications.

2. INTRODUCTION

The Thermolyzer™ technology is a highly-modified pyrolysis system, Figure 1, that converts all types of hydrocarbon-containing wastes into a fuel gas suitable for co-generation or synfuels, and “char”. This novel technology overcomes the limitations of previous pyrolysis process. First, it is a continuous, oxygen- free process meaning it operates 24/7.[1] Secondly, all hazardous oils and tars are turned into fuel gas. In this manner toxins are removed, and the process is more efficient. The process is halogen-tolerant. Halogens present in the recycled materials are converted to salts that can safely be removed in the waste water. Additionally, no measurable toxic dioxins or furans are created in comparison to other pyrolysis or incineration processes with halogens present. The clean fuel gas that is created is so clean that it can be used directly in gas turbines to generate electricity.

Figure 1. Photo of the pilot Thermolyzer^{TM} line located in Forst, Germany

One reason this process was selected for trial it the flexibility it has to process a variety of End-of-Life (EOL) materials. Hydrocarbon-containing materials which can be used as feedstocks include tires, all seven grades of plastics, carpet, wood, electronics waste, automobile shredder residue, and Fiber Reinforced Polymer (FRP) composites. The energy content of the produced gas will depend upon the available energy in any of the feedstocks. The char that is produced also depends upon the feedstock selected. For wood products, the char can be used as a soil amendment. If tires or composites are used, the char consists of steel and carbon black from tires or valuable fibers from composites. From scrap circuit boards, the char contains yields of metals (gold, silver, copper, palladium, etc.). The

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[1] Brandhorst, Henry W., Jr., “Thermolyzer Technology – a Revolutionary Change in WTE Processing,“ *AIAA Propulsion and Energy Forum*, 19-22 August 2019, Indianapolis IN, http://arc.aiaa.org, DOI: 10.2514/6.2019-4159.

Thermolyzer^{TM} operates with the recoverable energy in the polymers that would otherwise be lost to decay.

With abundant, high energy content feedstocks like plastics, carpet, or tires the primary output of the Thermolyzer^{TM} system is capable of providing clean fuel gas which can be used directly in burners for process heating, or in turbines or a reciprocating engine for electricity generation. This gas has been approved for use in gas turbines from commercial suppliers such as Solar and Siemens. The technology meets stringent California as well as German air emissions requirements. With composites, there will be just enough recoverable energy contained within the polymers to continuously operate the system so long as the feedstock is supplied. The char will consist of the carbon and glass fibers and some carbon char that can be removed.

3. BACKGROUND

Composite materials are only 1-2% of the greater materials market volume[2] as illustrated in Fig. 2.

One of the potential obstacles for growth of composites is the need to improve sustainability through reducing embodied energy with manufacturing productivity of composite processes and reducing waste going to landfill. This includes the End-of-Life (EoL) materials and manufacturing process scrap.

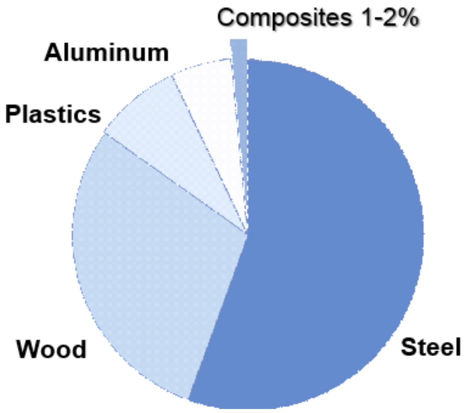

Figure 2. Composites share of global materials market.

Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) composites save energy through light-weighting in transportation which reduces both fuel usage and emissions. The domestic production costs of composites have the potential to improve with higher volume and/or the ability for productivity through lower tooling cost, and part consolidation, the reduction of waste, and an offset from recycling.

The specific strength of composite materials compares favorably with traditional metals as shown in Table 1, and will grow in favor as costs decline. Reductions in the embodied energy of composite materials will further improve their energy efficiency versus other materials for specific strength and modulus.

Glass and carbon fibers require a huge amount of energy to produce originally. Recovery of the glass or carbon fibers from the EOL composite saves that huge amount of energy required to produce these virgin materials. The ThermolyzerTM process uses embodied energy from the polyester or epoxy polymers to heat the primary and secondary reactors. The net result is that using the embodied energy from the composite resins in the recovery process will be significantly less than the energy needed to produce the original (virgin) glass or carbon fibers. The controlled pyrolysis technology of the Thermolyzer^{TM} is one approach which enables recovery of both this energy and monetary value in the recycled fiber.

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[2] Hartman, Dave, "Advances in Reinforcement Materials (Glass Fiber Materials), Owens Corning Composite Solutions," *Composites and Advanced Materials Expo (CAMX)*, Orlando, FL, October 13-16, 2014, https://www.slideshare.net/OwensCorningComposites/glass-fiber-reinforcements-advances-camx2014f.

Table 1. Material specific strength normalized by cost and embodied energy (Owens Corning)

	Glass Fiber	GFRP (0.6 Vf)	Carbon Fiber	CFRP (0.6 Vf)	Steel	Aluminum
Embodied Energy (MJ/kg)	27	33-45	183	236-280	45	227
Domestic Production Cost ($/kg)		2.50		27.00	0.50	2.10
Specific Strength (kNm/kg)		190		400	38	130
Specific Strength per Cost (kNm/$)		76		15	76	62
Specific Strength per Energy (kNm/MJ)		4.9		1.6	0.84	0.57

The composite materials industry is a multi-tiered, multi-material industry employing millions of workers across the U.S. economy. The diversity of composite materials creates an additional challenge for recyclers. This project selected representative composite waste streams from the energy and transportation supply chain as shown in Fig. 3. For transportation, the business model focused on the manufacturing source of scrap from the SMC composite molded part. SMC scrap comes from multiple sources: the molder, the OEM or automotive shredded residue (ASR), and the body repair shop. There are four different types of SMC for consideration: low density, structural, Class A highly filled calcium carbonate, and hybrid GF/CF fiber, which are further defined by resin formulation. The SMC manufacturers, represented by CSP, A. Schulman, John Deere, and others have used solid waste disposal, cement lime kiln recovery of energy and inorganic materials, as well as incineration. The question posed was whether the use of cost effective shredding for feeding SMC scrap from the manufacturer to a controlled pyrolysis process with potential to capture syngas and residual fiber, offered a reasonable value proposition.

For energy from wind turbine blades, the composite blade typically consists of glass and/or carbon fiber, polyester or epoxy matrix, sandwich core materials closed cell polymer foam or end-grain balsa wood, polyurethane bonded joints and coating, metal root fasteners and lightning conductors. As turbine blades grow in length for lower cost of energy (COE), so does the amount of material required to manufacture the blades. For each kilowatt (kW) installed, about 10 kg of rotor blade material is used. A 7.5 megawatt (MW) turbine would have about 75 tonnes of blade material.[3] Wind turbine blades are predicted to have a lifecycle of between 15 and 25 years, depending on the application and location. Twenty years from now approximately 350,000 annual tonnes of rotor blade material is estimated for end-of-life scrap on a global basis. The business model evaluation in this study includes an assessment of Life Cycle Analysis (LCA) from both the GE blade manufacturer perspective of composite fabrication waste and the GE OEM partnership for the repowering of wind farms and end-of-life composite blade waste. This assumes blade composite fabrication and EoL waste are represented by the range of trial materials in Fig. 3.

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[3] https://www.wind-watch.org/documents/recycling-wind-blades/

The primary project objective was to evaluate and validate the conditions that enable a successful recycling business case by optimizing feedstock and operational parameters for controlled pyrolysis. Fig. 3 illustrates the material waste streams that were studied for mass and energy balance input to a LCA and assessment of the value of carbon and glass fiber recycling in reducing embodied energy of composite materials. This information also supported the techno-economic evaluation of the value proposition that would lead to a successful business model. The ultimate vision was deployment of this technology throughout the U.S. and to contribute significantly to IACMI's goal of 80% composite recyclability in five years by converting composite EoL scrap into marketable, value-added products.

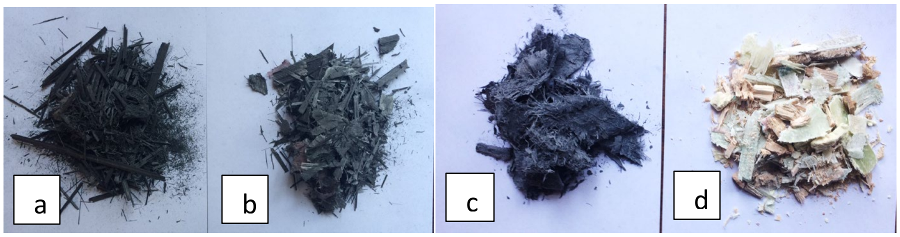

Figure 3. Shredded composite materials undergoing controlled pyrolysis in the IACMI Technical Collaboration Project: a: CF epoxy wind blade laminate (GE); b: GF/CF epoxy hybrid (John Deere); c: GF PE/VE automotive SMC (CSP); d: GF epoxy balsa/PVC foam wind blade (GE).

The value proposition depends on the utility and desirability of recycled composite materials, for example:

- Composite recycling is less expensive than landfill through re-use of recovered materials, given appropriate scale and supply chain;
- Recycled materials containing a blend of recycled glass and carbon fiber have utility with intermediate properties at a reasonable cost illustrated in Figure 4;
- Recycled composites and/or fibers could create demand for a lower-cost feedstock in a range of products in the composites industry;
- Recycled fibers could be washed and treated to improve processing and strength; and
- Recycled fibers could be blended in bulk molding compounds (BMC), Injection Molding or Extrusion Compression with the polymer matrix through continuous screw shearing processes for shearing fiber to critical length of 200 to 1000 micron for good matrix shear strength and dimensional stability.

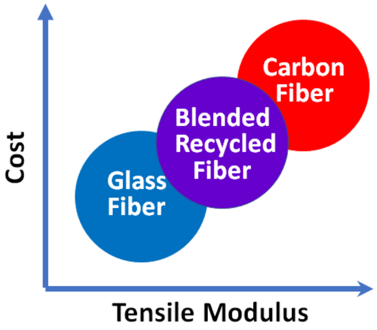

Figure 4. Potential value proposition for low-cost recycled materials, featuring blended glass and carbon fibers.

Fig. 5 shows the feed of continuous fiber along with polymer and Fig. 4 blended recycled fiber which would increase strength and elastic modulus in extrusion compression processing of charges to yield materials for compression molding of automotive components. The specific modulus and specific strength relationship of discrete random fiber composites and metals are comparable, as shown in Fig. 6. Thus, selective incorporation of recycled carbon and glass fibers in discrete random FRP composites make them competitive for automotive component lightweighting applications.

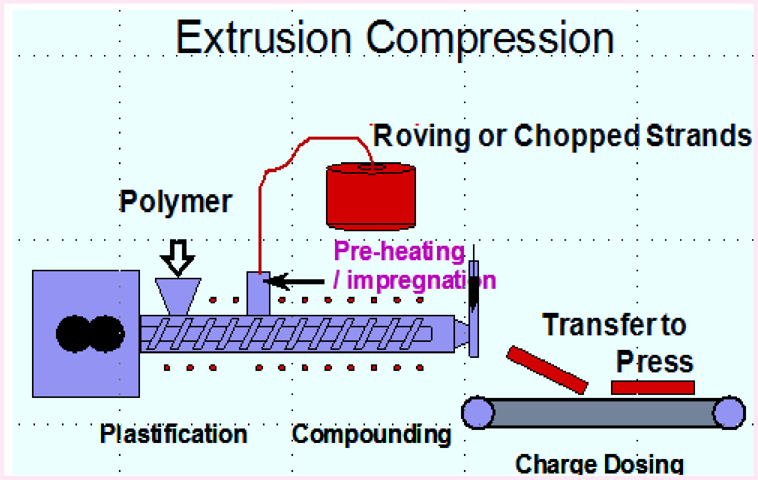

Figure 5. Recycled fiber fed with polymer pellets in extrusion hopper (arrow) for shearing to consistent length

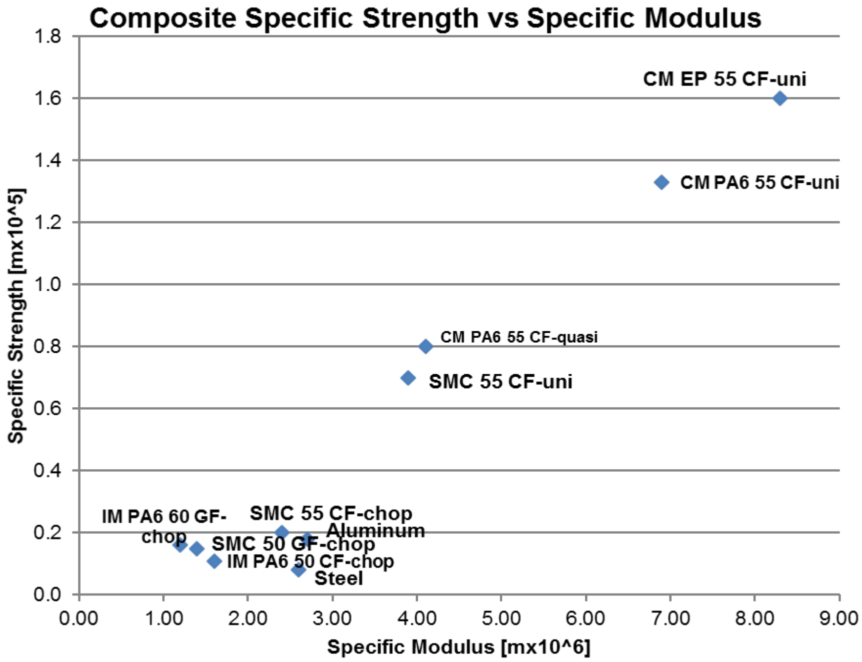

Figure 6. FRP Composite material comparison of random chopped glass and carbon fiber in SMC and IM PA6, uni-directional fiber in SMC, CM PA6 or CM epoxy versus aluminum and steel weight-performance (Owens Corning).

4. RESULTS AND DISCUSSION

Pyrolysis Trials

The pyrolysis trials of the Fig. 3 waste streams were conducted on a 4 ton/day capacity Thermolyzer^{TM} pilot unit over March 2018. The project deliverable LCA and TEA were derived from the mass and energy balance for the following trial materials data:

- process material input and output masses
- process energy inputs and outputs
- water consumed
- air emissions generated
- waste (including wastewater) generated including treatment (i.e., method of disposal)
- inbound and outbound transportation (distance and mode) of materials consumed and produced.

In the trials, the processing issues of the composite waste streams were primarily from the intermingling (i.e. bird's nesting behavior) of fibers after removal of organic material. Key observations from the trials include:

- The goal was to demonstrate handling of the composite waste streams to gasify the cured FRP composite and render the fiber useable to recover fiber properties. To accomplish this goal, the reactor system had to balance temperatures and dwell times for each waste stream.
- In processing the carbon-epoxy spar cap material from GE, the team discovered that the fibers became quite fluffy when all the polymeric materials were removed. These fibers became entangled and plugged portions of the primary reactor. The reactor was cooled down and carbon fibers all removed manually.
- The John Deere CF/GF hybrid composites waste stream flowed more consistently, and the fibers were easily collected. The CSP SMC-GF and GE Wind Turbine Blade GF and balsa/foam appeared to run the best in the process.
- Observation of the residual fiber with char indicated that appropriate washing, handling and processing is important for potential fiber reuse in composite applications such as bulk molding compounds (BMC) or extruded thermoplastics, because char can interfere with both uniform fiber re-dispersion and fiber-matrix interfacing.

The flowing positive outcomes resulted from the trials:

- The fibers can be processed, and the temperature/dwell time conditions can be met. The carbon fiber plugging in the first test can be overcome by modifying the output of secondary reactor into a twin-screw configuration or running carbon fiber together with glass fiber and/or other bulk organics.
- The resulting syngas has an energy content of >400 Btu/cu. ft. which is enough for the system to run on its own generated gas.

Life Cycle Analysis

The preliminary LCA considered staging above ground during the sorting and collection phase of shredded glass and carbon fiber reinforced polymer EoL waste. In this scenario, a higher volume of glass fiber EoL composites would either be:

1) Shredded and transported to a cement kiln for material and energy recover, or
2) Ground, washed/treated, and re-used in automotive under-carriage, railroad ties, or wind blade passive actuators.
3) Alternatively, glass/carbon hybrids at appropriate mix from above ground storage and staging, could bring higher value and are evaluated in the TEA along with residual carbon fiber shred.

The following examples were evaluated to benchmark recycling business models and establish a baseline for controlled pyrolysis. The LCA included a focus on GE blade manufacturer scrap with emphasis on EoL analysis for wind blade composite embodied energy. Five different business models were benchmarked:

1. Wind blade life warranty insurance extended from 15 year to 20 or 25-year life (baseline).
2. FRP Composite blade scrap shredded and re-used at wind farm site in turbine concrete foundation.
3. Bulk ship shredded composite to re-use at regional conversion site in applications like railroad ties.
4. Bulk ship shredded composite to regional controlled pyrolysis energy (syngas) and fiber recovery for re-use in new composite application or insulation.
5. Bulk ship shredded composite to cement lime kiln for energy recovery and silica filler enrichment of concrete fracture toughness (infrastructure).

The LCA allowed the appropriate input needed for techno-economic analysis and business model options:

1. **Wind blade life warranty insurance extended from 15-year to 20 or 25-year life (baseline) and for certain designs could be extended to 40-year life:** This significantly reduces carbon footprint impact as service life is extended. To determine the impact of extending the service life of a wind turbine blade, the global warming potential (GWP) impact from construction of a 2 MW onshore wind turbine was determined using the eco-invent v3.3 system model process, using eco-invent database version 3.3 from Karin Treyer, Paul Scherrer Institute, with parameters for wind turbine construction, 2MW, onshore, GLO, Allocation, and cut-off by classification.[4] The turbine blade model is based on the Vestas V80/2 MW turbine, which has 3 rotor blades. Using the TRACI v2.1 impact assessment methodology built into the TRACI LCA software tools,[5] the GWP impact of the turbine has been calculated to be 1,130,771 kg CO_2e of which 191,700 kg CO_2e can be attributed to the rotor blades (63,900 kg CO_2e/blade). Assuming a 15-yr blade service life, a GWP impact of 4,260 kg CO_2e/blade·yr has been used as a baseline to compare scenarios in which the service life is extended to 20 years and 25 years. These results and the avoided GWP impact under each of these scenarios are summarized below:

Table 2. Avoided GWP results

Service life of turbine blade	*15 -yr (baseline)*	*20 -yr*	*25 -yr*
GWP (kg CO2e/blade·yr)	4,260	3,195	2,556
Avoided emissions vs baseline (kg CO2e/blade·yr)	0	-1,065	-1,704
Avoided emissions (% reduction from baseline)	0%	-25%	-40%

2. **FRP Composite blade scrap shredded and re-used at wind farm site in turbine concrete base foundation:** It was sought to determine both the economic benefit and avoided GWP impact

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[4] https://www.wind-watch.org/documents/recycling-wind-blades/

[5] https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

of recycling composite blade material during the decommissioning of wind turbines as composite aggregate for use in new concrete foundations during a remediation and reconstruction phase of wind farms. The master's thesis entitled "Recycling wind turbine blade composite material as aggregate in concrete," conducted by Tyler Fox at Iowa State University Graduate Theses and Dissertations in 2016[6] was reviewed, which indicates a potential benefit of this particular end of service life solution for the recycling of composite wind blade material. Although the technical performance and feasibility of concrete produced with composite aggregate warrant further investigation, the study indicates both economic and environmental benefits when recycling composite material in this manner. Tables 3 and 4, reproduced from Tables 6 and 7 of the thesis, indicate that a cost of $62.72 and emissions of 1.0 kg CO2 can be avoided per ton of composite aggregate produced.

Table 3. Cost avoidance per ton of composite aggregate produced

Total Cost avoidance per ton of composite aggregate produced	
Landfill	$ 61.00
Limestone aggregate	$ 9.89
Transporting composite aggregate to landfill	$ 7.80
Machinery mobilization cost	$ (15.97)
Total cost avoidance	$ 62.72

Table 4. CO2 emission per ton of composite aggregate produced

CO2 avoidance or production	**lb (kg)**
Avoidance from Limestone	4.0 (1.8)
Avoidance from landfilling composite	2.7 (1.2)
Avoidance from transporting composite to landfill	17.2 (7.8)
Production from transportation of chipping machine	19.0 (8.6)
Production from use of chipping machine	2.5 (1.1)
Total emissions reduction	23.8 (10.8)
Total emission production	21.5 (9.8)
Total emission avoidance	2.3 (1.0)

3. **Bulk ship composite shred for re-use at regional conversion site in new application like C2 railroad ties:** As this disposal scenario is a novel application, which is currently under development, it is recommended to follow-up with NICE Rail Products for benchmarking the benefits of composite railroad ties.[7]

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[6] http://lib.dr.iastate.edu/etd/15159

[7] https://www.voestalpine.com/nortrak/en/news/voestalpine-Nortrak-and-NICE-Rail-Products-Launch-Evertrak-Composite-Tie/

4. **Bulk ship composite shred to regional controlled pyrolysis energy (syngas) and fiber recovery for re-use in new application:** Controlled pyrolysis of composite materials for both energy and fiber recovery is a novel application and is potentially a beneficial solution. In 2018 the project team recommended process trials of composite scrap and data collection for further analyses in order to benchmark pyrolysis to recycle composite material.
5. **Bulk ship composite shred to cement lime kiln for energy recovery and silica filler enrichment of concrete fracture toughness (infrastructure):** Additional research and further literature review is needed to determine the potential benefit of using waste composite material as energy and material feedstock for cement clinker production.

Techno-Economic Analysis

From a business perspective, the global CFRP market is expected to reach $20.2 billion by 2022, supported by a CAGR of 8.1% since 2014,[8] while the global GFRP market is expected to grow from 43.9 billion in 2017 to 59.9 billion by 2022 at a CAGR of 6.4%.[9] If the fibers from scrap materials can be recovered successfully and find utility in marketable products it would help grow the industry as well as create new jobs. CFRP parts contain 25-40% carbon fiber at $12-$28/lb and GFRP contain 30-60% glass fiber at $2.00-4.50/lb of composite material. Economic recovery of these fibers will enable increased usage of CFRP with lower embodied energy and lower costs for certain applications.

In addition, about 43% of all CFRP applications contain halogens for corrosion, chemical resistance or flammability requirements. High temperature processes (>400 ºC) produce unacceptably high levels of halogenated dioxins or furans. Disposal of the current waste stream is also costly due to these contaminants, so a process that enables recovery and eliminates disposal of hazardous materials in a landfill will have a large impact. Any waste that goes to a landfill amounts to wasted energy from the convertible organics in the mix.

Fortunately, thermolysis processing can break down these composite materials, turning the organic binders into an energy rich synthesis gas while recovering the glass or carbon fibers from the matrix. One of the most versatile technologies available is the Thermolyzer™, which has been described above.

What are the potential economic impacts of a 4 ton/day Thermolyzer™ system designed for composites? This system, designed for processing composites, would process the feedstock continuously (24/7) with a team of 12 employees. The cost for the plant would be on the order $4-7 million including shredding, processing, appropriate building, storage, and office space. Assuming 80% fiber recovery efficiency: CFRP = (0.8 x $24,000/ton x 4 TPD x 344 days' x 33%) = $8.7 Million/yr. and for GFRP = (0.8 X $5000/ton x 4 TPD x 344 days' x 40%) = $2.2 Million/yr. The 80% fiber recovery efficiency value represents typical process energy balances in any chemical or thermal process. We believe, based on the results of our trials, that the process efficiency could move closer to 90% when operated on a continuous basis. The 10% loss is to be expected from basic thermodynamic processing losses.

Depending on the number of systems, the employment impact can be huge. For example, if there are

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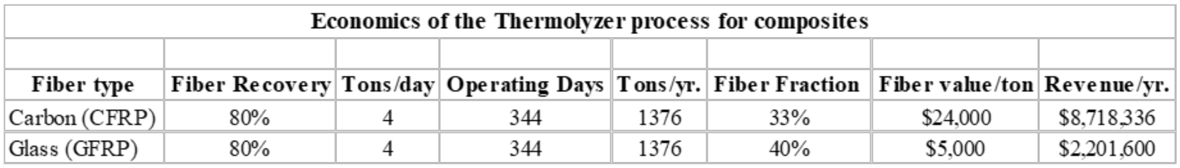
[8] https://www.alliedmarketresearch.com/carbon-fiber-reinforced-plastic-cfrp-market

[9] https://markets.businessinsider.com/news/stocks/global-gfrp-composites-market-2018-2022-increasing-number-of-wind-energy-capacity-installations-is-driving-the-market-1014142936#:~:text=The%20global%20Glass%20Fiber%20Reinforced%20Plastics%20%28GFRP%29%20composites,a%20CAGR%20of%206.4%25%20from%202017%20to%202022.

1.0 million tons/yr. of combined U.S. composites, there would be a need for 727 4 ton/day systems. With 12 people/system (24 hr./day operation) about 8,700 employees would be needed. Other employees would be added in sorting, dismantling, transporting waste materials plus site support activities. This may be an additional 8-15 people per system. Thermolyzer™ systems come in 22, 44, 88 and 120 TPD versions. Staffing would not change significantly with larger systems.

Table 5. Example Thermolyzer™ economics calculations summary



Economics of the Thermolyzer process for composites

Fiber type	Fiber Recovery	Tons/day	Operating Days	Tons/yr.	Fiber Fraction	Fiber value/ton	Revenue/yr.
Carbon (CFRP)	80%	4	344	1376	33%	$24,000	$8,718,336
Glass (GFRP)	80%	4	344	1376	40%	$5,000	$2,201,600

A potential obstacle to the large-scale recycling of composites is that both carbon and glass fibers are known to suffer varying extents of mechanical degradation during pyrolysis processing [1,2]. It is therefore important to assess process conditions and capabilities to determine if glass and carbon fiber can be recovered with sufficient mechanical (and hence economic) value to justify composite recycling. Also of interest is whether or not gases evolved from composite scrap possess sufficient energy content to sustain a pyrolysis process as well as the effects other inorganic composite fillers might have on the overall process.

Thus, a pilot test was conducted, in cooperation with the ACMA partners, to process the following materials in a 4 ton/day pilot plant in Forst, Germany. Four materials were selected: wind turbine blade composites (both glass and carbon fiber-based), glass fiber scrap, and a mixture of composites. Mass and energy balances were provided and the resulting char (e.g. glass or carbon fibers) was returned to industry for evaluation of their suitability for reuse. Industry observers were present at the tests. Approximately 500-1000 lbs. of each of the materials was provided for each test. The exact test plan was worked out in collaboration with the wider project team.

Thermal and mechanical characterization

The project team chose a few select materials that would be representative of the wider composite waste streams. This was done by identifying 5 general categories into which most composite materials fit: 1) glass fiber reinforced polyester/vinylesters, 2) glass fiber reinforced epoxies, 3) carbon fiber reinforced epoxies, 4) hybrid glass and carbon fiber reinforced epoxies, and 5) uncured molding compounds/prepreg. Thermoplastics were ignored when developing these categories as they can, at least in principle, already be recycled through other means. Scrap materials were sourced for the first 4 categories: 1) a glass fiber polyester and vinylester blend SMC scrap, 2) EoL glass fiber epoxy wind turbine blades (including support core materials such as balsa wood and PVC foam), 3) carbon fiber epoxy prepreg wind blade spar caps, and 4) a glass fiber and carbon fiber prepreg frame used in industrial machinery. Category 5 was ignored as in the worst case such material could easily be allowed to cure at which point it would fit into one of the other four.

All test materials were size reduced (glass fiber specimens to 2 inches carbon fiber specimens to 1 inch) via shredding to both allow the materials to be fed into the Thermolyzer™ as well as provide control over the length of the recovered fibers. Before large-scale testing, all materials were subjected to thermogravimetric analysis (TGA) under inert atmosphere (nitrogen) to determine temperature ranges needed for complete sample pyrolysis. TGA results suggested that, while some of the organic components would begin slowly breaking down near 350°C, a temperature of at least ~450°C was necessary to ensure complete organic material breakdown in each of the selected materials. A best case, minimally aggressive pyrolysis (~22 minutes at 350°C followed by ~11 minutes at 450°C, excluding heating periods) was conducted at lab scale using a tube furnace to determine a relative upper bound for expected recovered fiber mechanical performance.

The baseline reference properties used for comparison with the recycled fibers were those measured from the virgin glass fiber that served as the input feedstock for the SMC sample and the calculated virgin fiber properties from the spar cap prepreg material specification sheet. Single filament tests were conducted at ORNL based off ASTM C1557-14. Nominally 20 test runs per condition were used, although because not every single test was successful (e.g., fiber slip in grip) the true *n* tests used for parameter calculations can dip below this value; supplemental tests to increase total n could not be used because variations in load frame system compliance between fiber testing sessions were sufficient to create trends in the fitted data residuals. An MTS Alliance RT/5 load frame with 2N load cell was used for mechanical data collection, and an Olympus BX50 optical microscope was used to determine fiber diameters for stress calculations. The single filament tensile test results for each fiber sample, summarized in Table 6, indicate that the recovered carbon fiber remained comparatively high strength after pyrolysis processing; however, the recovered glass fibers suffered significant reductions in tensile strength, despite Young's modulus remaining unaffected. Worth noting though is that filament tests of glass fibers recovered from the SMC sample shreds prior to pyrolysis processing showed a pre-existing drop in fiber strength from virgin properties. This indicates that the pyrolysis process does not cause most of the fiber strength reduction and, therefore, the damage must occur earlier in the virgin composite production and shredding processes. While there would appear to be a significant drop in carbon fiber Young's modulus, it is important to remember that these modulus results have not been corrected for machine compliance (which proved difficult with the small fibers recovered from the process), and so the real Young's moduli of the pyrolyzed fiber may be higher than the observed value. This effect would not be as significant for the glass fiber specimens as their Young's modulus is an order of magnitude lower. Based on what machine compliance values could be determined, it is estimated that this effect could be responsible for as much as half the observed modulus decline in the CF specimens.

Table 6. Averaged results from uniaxial tension tests on single filaments recovered from material samples collected after Lab Scale Pyrolysis. The "Virgin Carbon Fiber" specimen results are present to indicate they are not experimentally measured, rather calculated from spec sheet data.

Average Results of Lab Scale Single Filament Tensile Testing				
Test Specimen Materials	Fracture Strength		Young's Modulus	
	Strength (MPa)	%Dif. from Virgin	Modulus (GPa)	%Dif. from Virgin
Virgin Glass Fiber	2200	N/A	50	N/A
Virgin Carbon Fiber	(3100)	N/A	(210)	N/A
SMC (shredded) - GF	1500	-32	50	0
SMC - GF	1200	-45	50	0
Wind Blade - GF	1300	-41	50	0
Spar Cap - CF	2200	-29	140	-33
Hybrid Prepreg – GF	900	-60	50	0
Hybrid Prepreg – CF	2400	-23	130	-38

The main results from pilot plant operation with the composite material types are summarized as follows:

- The plant operation with each type of material was successful. The technology for thermal and chemical conversion of the matrix, as carried out in the pilot plant, was found to be suitable for processing the type of material with the restriction of the mechanical conveyance of the fiber body, which is formed by the disintegration of the composites. The conveying of the tangled fiber body requires technical measures on the conveying equipment, some of which have now been implemented and successfully tested.

- A fiber body containing carbon dust is produced, which can be further mechanically processed to obtain aligned fibers and separate the carbon dust. Except for the type of material, which contained PVC, the glass fiber/carbon content produced was 60 to 70% of the input quantity.
- A gas is produced that can be used to generate the required energy for the pyrolysis process.
- Samples taken for detection and analysis of dioxins proved that no dioxin is produced or that any dioxin present is decomposed in the process.
- The effects of the technology on the processes in the reactor and in gas scrubbing are explained in Appendix A.
- Four material types were processed in succession. During the transition from one type of material to the other, a back-mixing of the fiber components occurs in the transition phase despite mechanical cleaning of the apparatus, since the fiber body cannot be completely discharged.
- The operating behavior of the system has been demonstrated.
- The chemical and thermal processes examined are suitable for the objectives of material processing. Technical adaptation measures to the equipment are required for the conveying processes.

As expected, the fibers recovered from the Thermolyzer^{TM} pilot process were in general weaker than those produced under ideal lab scale conditions, summarized in Table 7. While degraded, the carbon fiber samples still exhibited relatively high mechanical properties indicating the potential for reuse as composite reinforcement. Interestingly, the carbon fiber containing specimens appeared to fare better in the Thermolyzer^{TM} process than under the lab test conditions. Separate measurement of the glass and carbon fibers in the hybrid prepreg specimen proved too unreliable, and so the sample was averaged in aggregate with approximately double the number of filaments measured as compared to the other specimens; the lab scale results were averaged together for comparison. These aggregated averages indicate the hybrid specimen appeared to fare better in the Thermolyzer^{TM} process, likely due to the carbon fiber component. This suggests mixed recycled fiber feedstocks might be a viable way of stretching limited carbon fiber quantities and improving the value of recycled glass fiber feedstocks.

Of the two glass fiber specimens, the SMC sample fibers had become so weak that they were too fragile to even mount for mechanical testing. The glass fibers from the wind blade specimen fared slightly better with a measurable strength, admittedly much lower than the lab result. One potential reason for the difference in performance may be that the presence of the balsa wood/PVC foam chunks in the wind blade specimen were observed to help the wind blade specimen shreds flow better and more consistently through the reactor during processing. It was observed during pyrolysis processing that as the resin matrix is removed, the composite fibers have a tendency to form a bird's nest like consistency, inhibiting uniform bulk flow through the Thermolyzer^{TM} reactor. This suggests blending composite shreds with other chips of bio-based or plastic feedstock could help improve the final quality of recovered fibers (in addition to boosting produced fuel gas energy content). Another potential issue, as will be discussed in detail later, is that the Thermolyzer^{TM} appears to have contained significant metallic contamination from past reactor test runs that may have damaged the fibers nonuniformly during processing. Also of note is that the main and secondary reactor temperatures ended up being in the ~500-550°C range, which when coupled with the extended, uneven time of exposure in the reactor from flow issues (see Appendix A for details), means the samples experienced a relatively harsh thermal exposure for E-glass which would cause significant strength reduction.

Table 7. Averaged results from uniaxial tension tests on single filaments recovered from material samples collected after either lab scale pyrolysis or Thermolyzer^{TM} processing. The SMC glass fibers recovered

from the Thermolyzer$^{\text{TM}}$ process were too mechanically weak to mount and so could not be measured.

Comparison of Single Filament Tensile Results for Different Scale Pyrolysis Processing				
Test Specimen Materials	Fracture Strength (MPa)		Young's Modulus (GPa)	
	Lab test	Thermolyzer$^{\text{TM}}$	Lab test	Thermolyzer$^{\text{TM}}$
SMC - GF	1200	N/A	50	N/A
Wind Blade - GF	1300	600	50	70
Spar Cap - CF	2200	2200	140	170
Hybrid Prepreg – GF/CF	1500	1700	80	120

One unfortunate issue that emerged upon examination of the recovered Thermolyzer$^{\text{TM}}$ processed samples was the presence of significant contamination (see Fig. 7). Contamination was found in a variety of forms, from large metal shards and copper wiring to rust colored particles and elemental traces of bromine and aluminum on the recovered fiber surfaces. Despite attempts at purification through various industrial separation techniques, the project team was unable to completely remove the most obstructive metal contaminants without also disintegrating the desired fibers. This limited attempts at 2nd generation composite production to a few small proof of concept experiments.

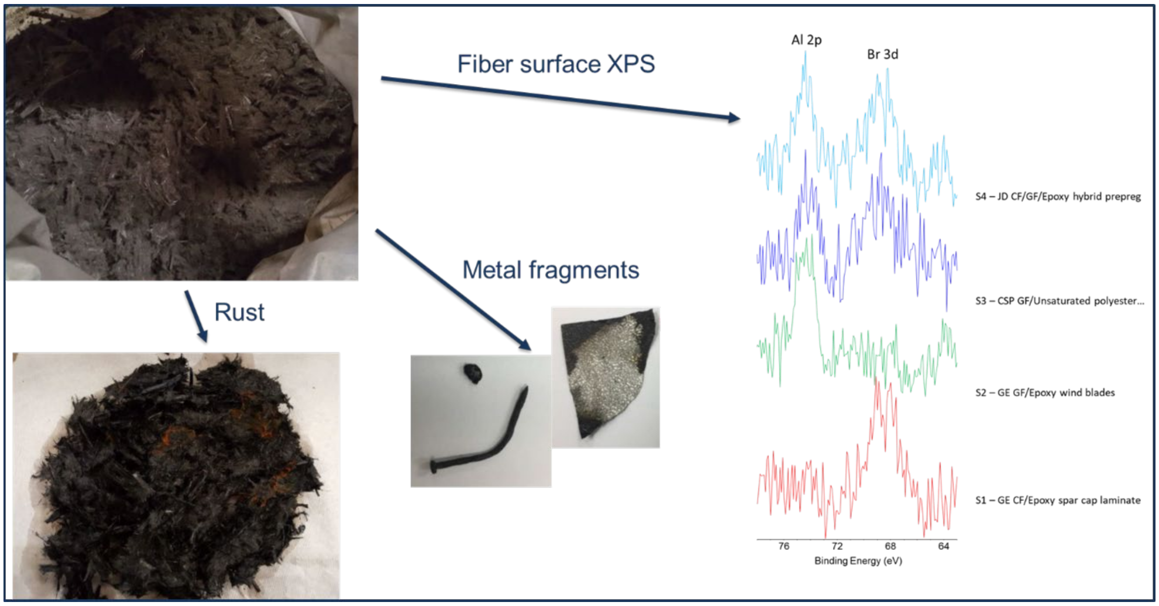


Figure 7. As-pyrolyzed fiber (upper left corner) from the Thermolyzer$^{\text{TM}}$ contained several different forms of contamination limiting 2nd generation composite research.

While large scale testing of composites with Thermolyzer$^{\text{TM}}$ recovered fibers was restricted by contaminant content, small scale testing was able to proceed through manual, hand-removal of the most inhibiting debris. One area examined was the re-dispersion of fibers in new polymer matrix phases. To establish a baseline for the performance of the as-pyrolyzed fiber (including char), small samples of material were mixed with polypropylene, nylon-6, and epoxy using a Brabender Intelli-torque Rheometer. Temperature and torque conditions are listed in Table 8. Polymer and fiber were loaded over the course of 5 minutes and given an additional 5 minutes to blend until torque equilibrium was met. The thermoplastic specimens were then molded into very thin sheets under 20,000 pounds-force to qualitatively gauge fiber dispersion via optical microscopy. The epoxy specimens were drop cast onto glass slides and optically observed uncured. As can be seen in Fig. 8-10, as-pyrolyzed fibers did not appear to uniformly re-disperse when compounded with the new resin systems. This would suggest the need to identify an appropriate method of char removal to eliminate clumping and allow better fiber dispersion. Preliminary attempts with sizing exposed as-pyrolyzed fibers exhibited the same issue, although with slight improvement. Char removal should also help with fiber re-sizing uniformity further improving potential re-dispersion.

Table 8. Shear mixing parameters used to disperse as-pyrolyzed fibers received from the Thermolyzer^{TM} process after manual separation of larger metallic contaminants.

As-pyrolyzed Fiber Shear Mixing Parameters		
Polymer Matrix	Temperature (°C)	Torque Range (N-m)
Polypropylene	220	20-40
Nylon-6	240	20-40
Epoxy	(no heat applied)	10-25

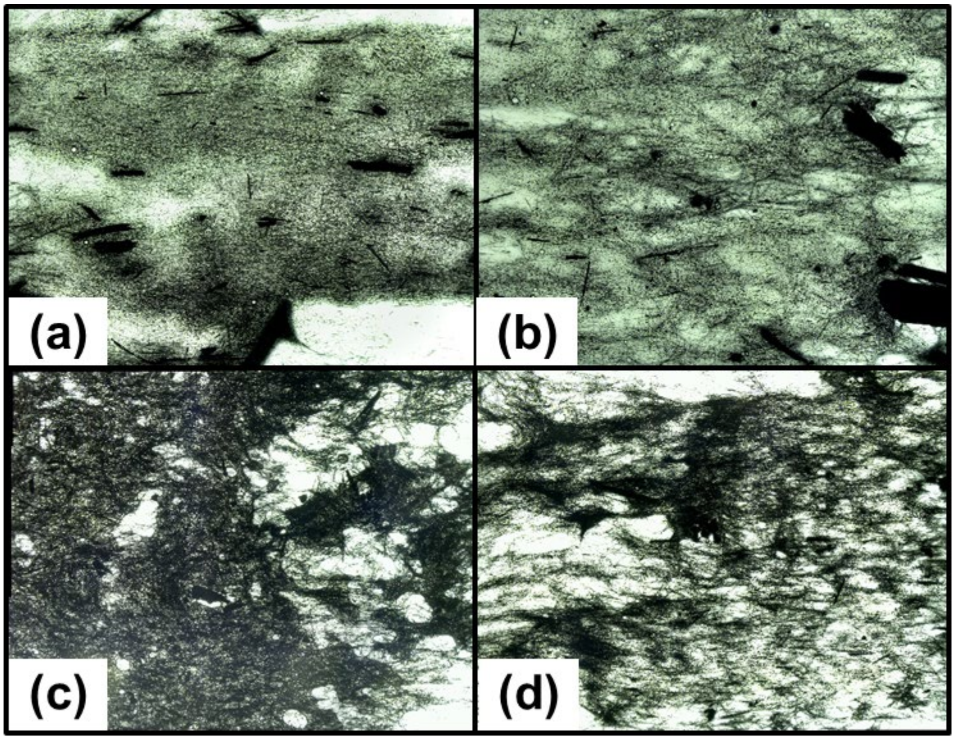


Figure 8. As-pyrolyzed Thermolyzer^{TM} recovered fibers, after hand removal of metallic contamination, in epoxy at 50x magnification: (a) SMC - GF, (b) Wind blade - GF, (c) Spar cap prepreg - CF, (d) Hybrid prepreg - GF/CF

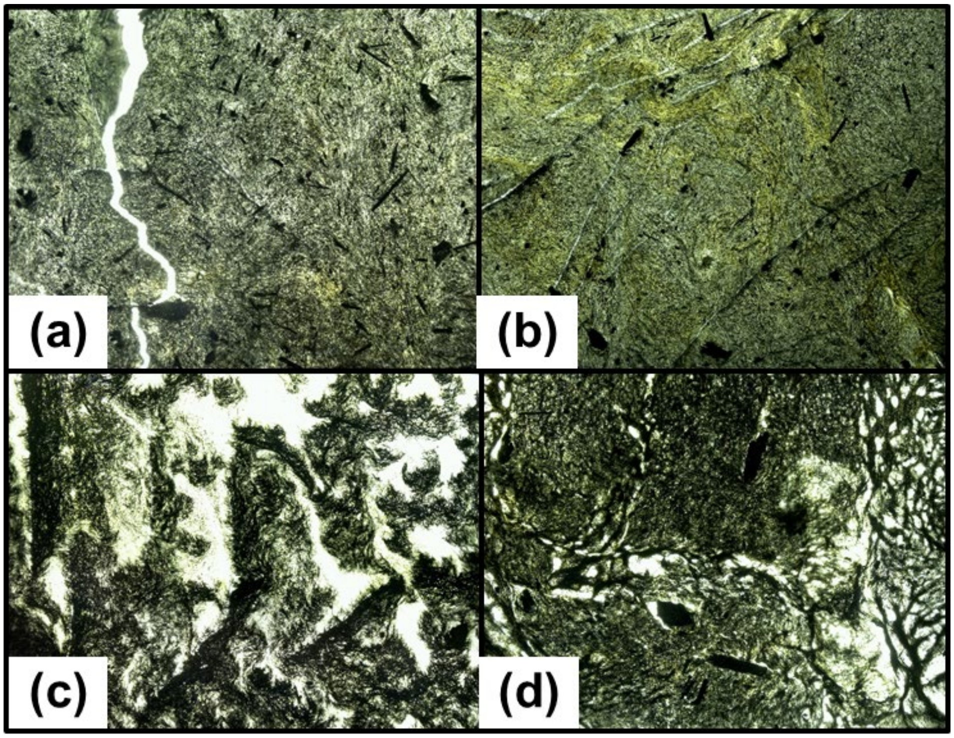


Figure 9. As-pyrolyzed Thermolyzer^{TM} recovered fibers, after hand removal of metallic contamination, in nylon-6 at 50x magnification: (a) SMC - GF, (b) Wind blade - GF, (c) Spar cap prepreg - CF, (d) Hybrid prepreg - GF/CF

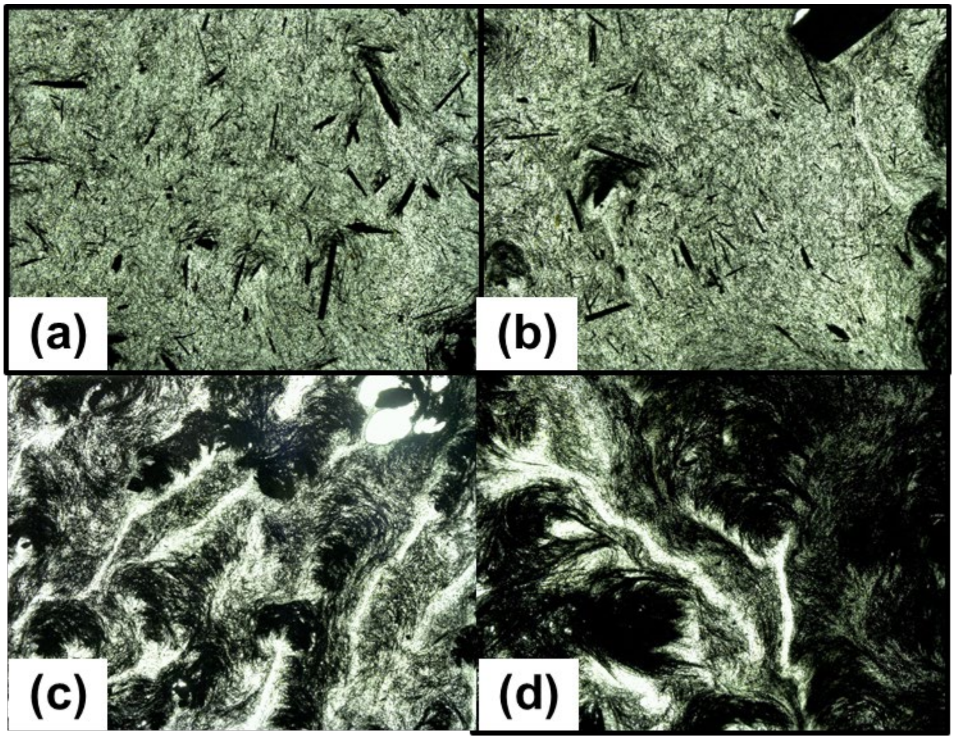


Figure 10. As-pyrolyzed Thermolyzer^{TM} recovered fibers, after hand removal of metallic contamination, in polypropylene at 50x magnification: (a) SMC - GF, (b) Wind blade - GF, (c) Spar cap prepreg - CF, (d) Hybrid prepreg - GF/CF

As-pyrolyzed fibers were also put through wet-laid nonwoven mat processing, to address and overcome both the contaminants issue and charred fiber redispersion problems. In this process, as-pyrolyzed fiber from the wind turbine blade (glass) and wind blade spar cap (carbon) samples were added to a large water bath and turbulently mixed with various surfactants and polypropylene fibers and then strained to produce nonwoven mats as shown in Fig. 11. The mats consisted of 20 wt% as-pyrolyzed fiber and 80 wt% polypropylene fibers. The mats were then compression molded by the following procedure: 1) Mold preheated to 175°C; 2) Mats loaded 2-3 at a time, being pressed at 4 tons for 10 minutes between each addition (total 30 minutes for all 10 layers); 3) Dwell for 20 minutes at 4 tons; 4) Dwell for 20 minutes at 8 tons; 5) Turned off heater to platens to cool down to 80°C for demolding. ASTM D638 mechanical test specimens were cut from the test panels and then subjected to uniaxial tension testing. The stress-strain curves (Fig. 12) from tested specimens (Fig. 13) indicated the following observations:

- Reinforcing fiber and polypropylene fiber lamina did not become fully consolidated during molding, resulting in delamination (especially in the glass fiber samples);
- The glass fiber wind blade sample mechanical failure appears controlled by the failure of glass fiber/polypropylene interface and the internal interfaces within the charred glass fiber bundles (especially in domains perpendicular to load);
- Carbon fiber spar cap sample mechanical failure was controlled by the lack of consolidation of the polypropylene fibers resulting in visible pullout.

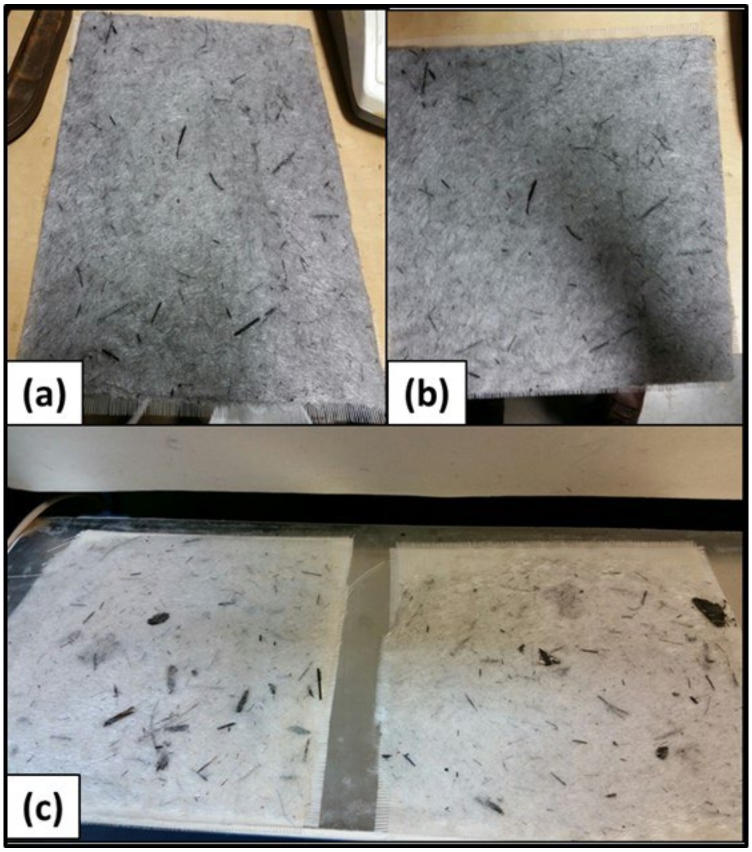


Figure 11. Wet-laid mats produced from Thermolyzer^{TM} reclaimed (a, b) carbon fiber and (c) glass fiber

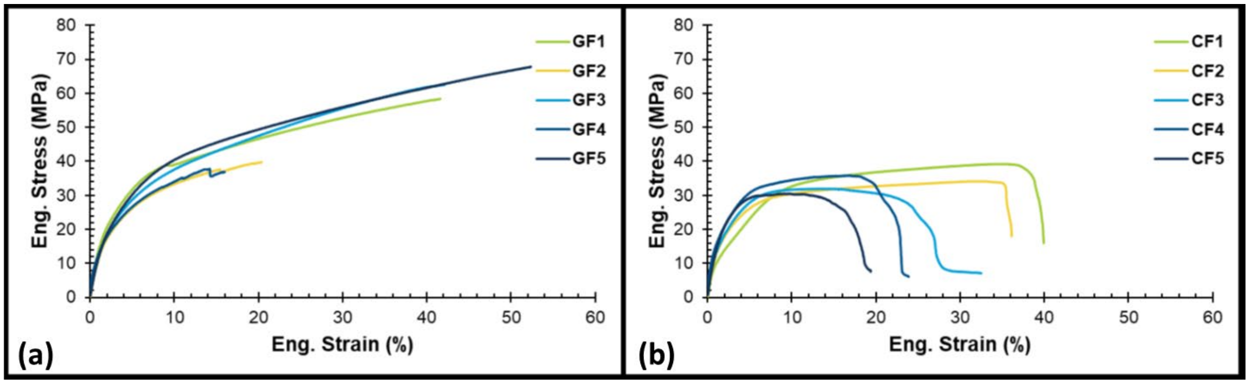


Figure 12. Engineering stress-strain curves for molded wetlaid composite specimens with 80 wt% polypropylene and 20 wt% Thermolyzer^{TM} as-pyrolyzed fiber: (a) Wind blade - GF; (b) Spar cap prepreg - CF

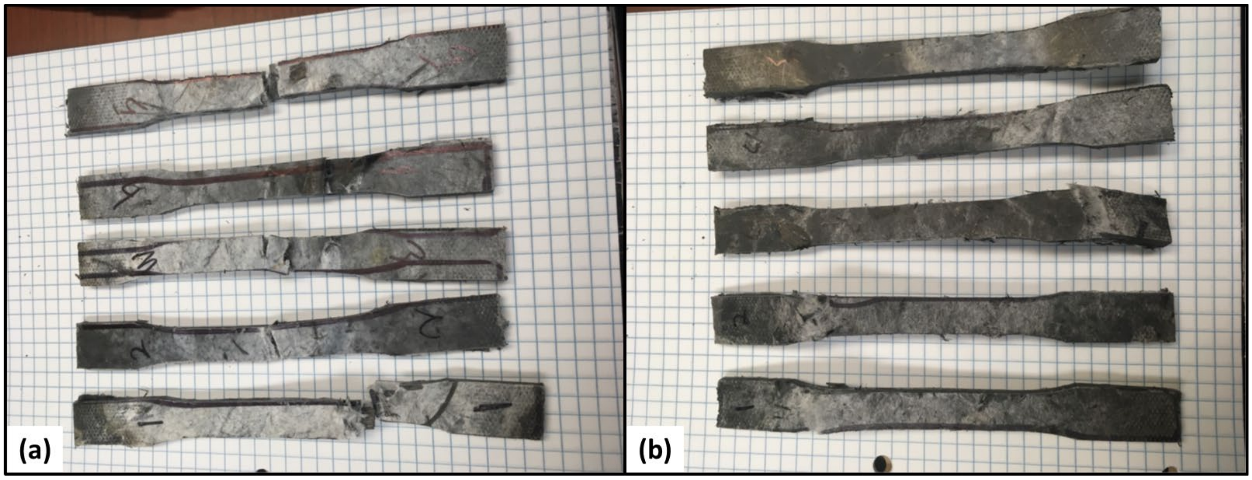


Figure 13. Molded wetlaid composite specimens (after tensile testing) with 80 wt% polypropylene and 20 wt% Thermolyzer^{TM} as-pyrolyzed fiber: (a) Wind blade - GF; (b) Spar cap prepreg – CF

LCA Modeling Method used for the Thermolyzer^{TM} assumptions and analysis:
The LCA considered a staging above ground for collection of, for example, automotive shred and wind turbine blade shred. A higher volume of glass fiber EoL composites would either be shred and transported to a cement kiln, or ground, washed, and re-used in wind turbine blade section, concrete platform, decking and fencing around the platform. Other glass/carbon hybrids at the appropriate mix from above ground storage and staging, which could bring a higher value proposition, were evaluated along with residual carbon fiber and glass fiber recovered with the Thermolyzer^{TM}. Fig. 14 sets boundary conditions and compares the glass and carbon FRP scrap scenarios evaluated in the LCA.

FRP waste sent for processing for recovery of fibers is assumed to have impacts from truck transportation (200 miles) and barge transportation (500 miles) to the processing location, washing of the recovered material, and shredding/grinding of the material for the process. An initial model was constructed by modifying a pyrolysis gasoline production process from NREL from the US-LCI database, as incorporated into the DATASMART v1 LCI package by Long Trail Sustainability for SimaPro v8.5.2. Place holder processes were filled with available data from the eco-invent 3.4 allocation, cut-off by classification – unit database as implemented in SimaPro v8.5.2. An additional model was constructed which eliminated more of the background data from the above modified Pygas model, such as incoming natural gas raw materials and associated transport, and focused on the available energy data from the trials. Both sets of models include recovered glass fiber and recovered carbon fiber as outputs. An FRP Waste Recycling process was also included as an output and was allocated the burden of the Thermolyzer^{TM} process to allow for comparison with the other waste treatment options. So, no impact was assigned to recovered energy or recovered glass and carbon fiber. The model focused on trial data was used as the basis for the subsequent analyses.

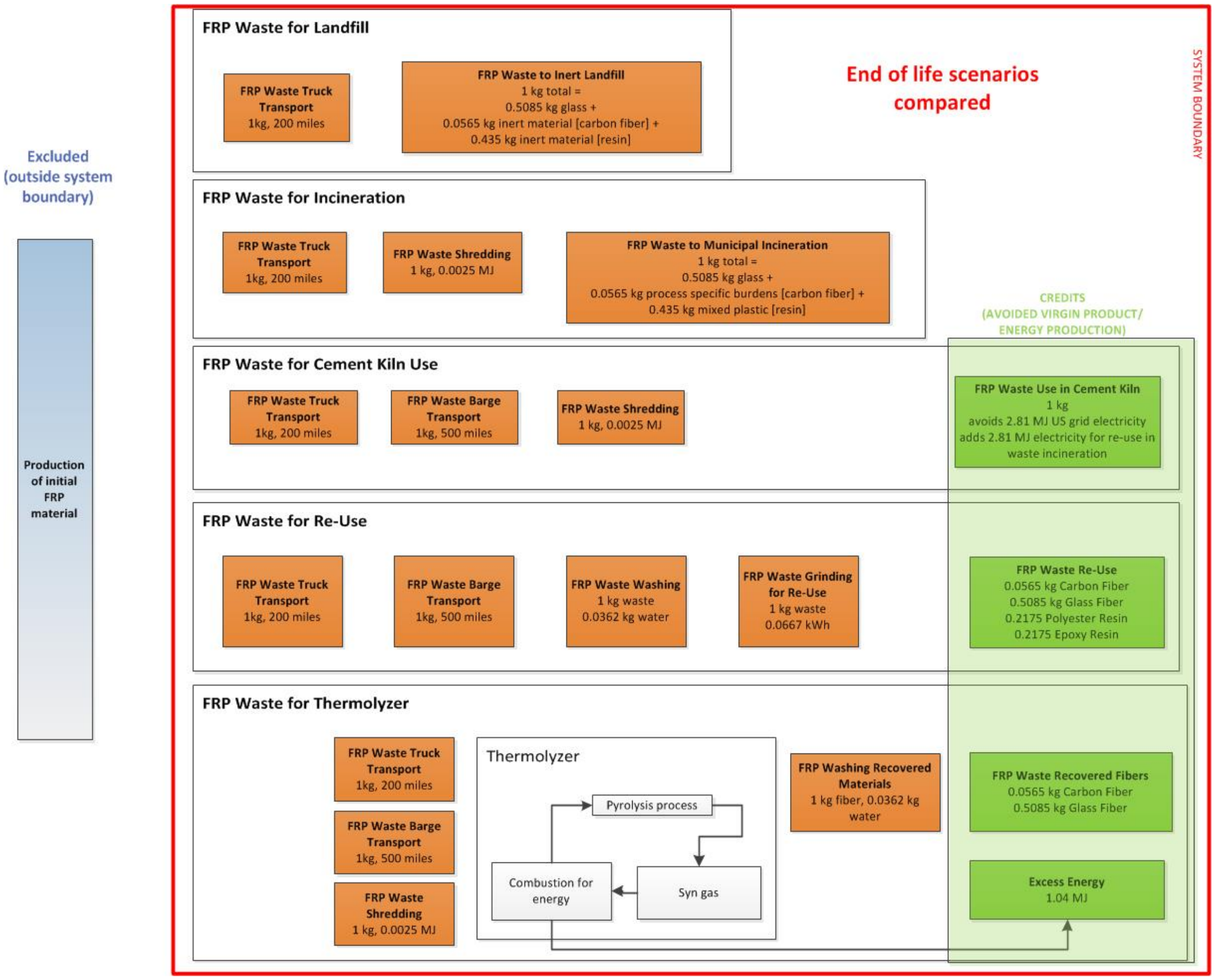


Figure 14. LCA system boundary for FRP waste end-of-life scenario comparison

Per CHZ, the recovery rates for carbon and glass fibers in the composite scrap materials were short of 100% of their initial weights in the input feedstock because they could not be converted further within the temperature range of the Thermolyzer^{TM} process. CHZ expects that a 10% loss of either glass or carbon fibers would be seen in the Thermolyzer^{TM} process. This means that glass fiber processing would have some of the fiber loss through the mechanical processing with fibers eroded, sheared or fractured to produce very small silicate fragments left in the char and physically unable to be recovered. The same is the case with carbon fibers: these fibers exposed to 500-600 C become brittle or friable. Fiber ends tend to fracture or shear into smaller silicate pieces left in the char. Resin components were converted to Syngas, similar to most plastics, at a rate of 90%, with 10% carbon from the resin left in the char together with the carbon and glass fibers. The generated Syngas was mostly consumed for internal heating and processing of the FRP feedstock. The LCA process comparison as waste treatment, without accounting for avoided products (i.e., displacing on-purpose products produced by the traditional manufacturing vs recycled production routes), was based on 1kg FRP scrap recycled for the Cumulative Energy Demand (CED) v1.10 total energy value, and for global warming impact in the Tool for Reduction and Assessment of Chemical and other environmental Impacts (TRACI) 2.1 v1.04 as implemented in SimaPro v8.5.2 used in Table 9.

The results of the Thermolyzer^{TM} model vary greatly depending on how the avoided products are applied. Since the Thermolyzer^{TM} is using the organic content from the waste to power the process, the process "electricity for reuse in municipal waste incineration only," was selected to represent the impacts. The energy is displacing grid electricity, so a version of the model was created that assumes US grid medium voltage, market group electricity (ecoinvent 3.4 cut-off) as an avoided product summarized in Table 10, for comparison of the different recycling approaches. Due to the significant "credit" from modeling this way, the analysis was also run without the avoided product to provide a clear understanding of the waste treatment method compared to the other scenarios. To compare the waste treatment aspect, it was necessary to alter the allocation of impact from the fibers to the waste treatment.

It is evident that giving credit to account for avoided grid electricity overwhelms other impacts. When examined without the credit, other than disposal by incineration, the results from TRACI show that transportation of the waste material continues to be a dominant impact in most categories, with GWP impacts from transport of 41% for Re-Use, 66% for Recycling in Thermolyzer^{TM} and 95% for Cement Kiln and Landfill. In Table 10 then it is no surprise that accounting for avoided grid electricity and avoided fiber products, shows the most significant effect on CED and TRACI for the Thermolyzer^{TM} process.

Table 9. LCA comparison of recycling processes without avoided products to determine total energy value and global warming equivalent

Process Comparison as Waste Treatment (without avoided products) based on 1kg FRP scrap	**Total Energy (CED) MJ**	**Global Warming (TRACI) kg CO2 eq**
FRP Waste to Landfill	0.67	0.05
FRP Waste to Incineration	1.05	**1.07**
FRP Waste to Cement Kiln	1.03	0.08
FRP Waste Re-Use	**1.74**	0.11
FRP Waste Recycling in Thermolyzer	1.02	0.08

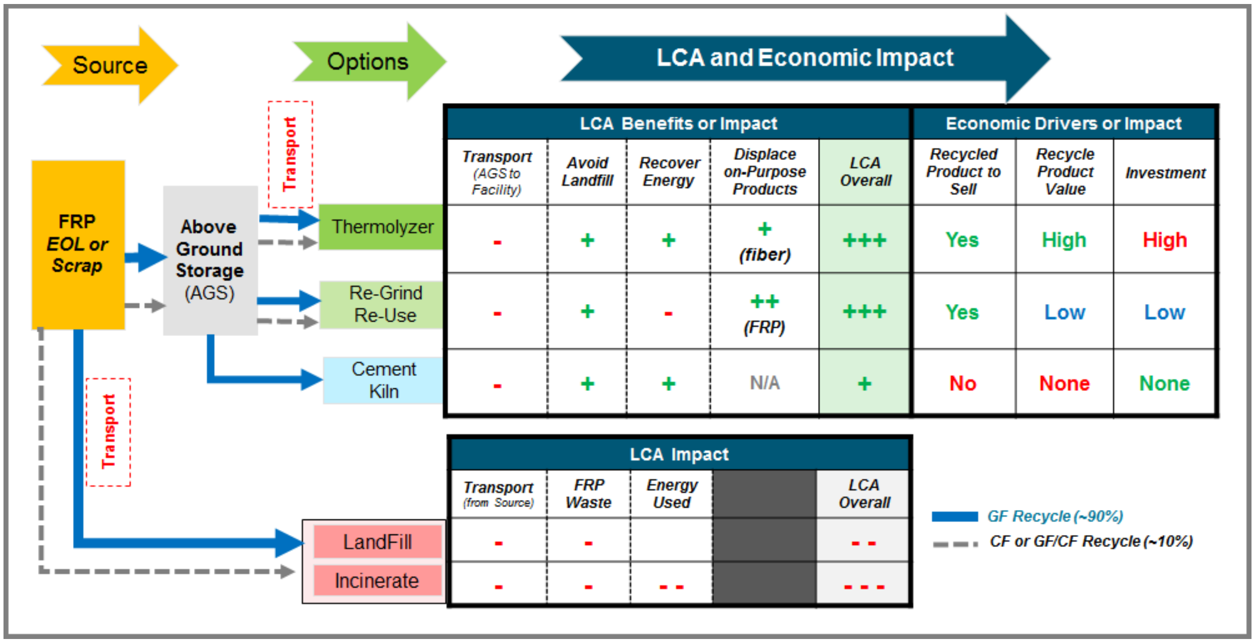
Table 10. LCA comparison of recycling processes with avoided new products to determine total energy value and global warming equivalent

Process Comparison with credits (avoided new products) based on 1kg FRP scrap	**Total Energy (CED) MJ**	**Global Warming (TRACI) kg CO2 eq**
FRP Waste to Landfill (no credit)	0.67	0.05
FRP Waste to Incineration (no credit)	**1.05**	**1.07**
FRP Waste to Cement Kiln (electricity credit)	-7.71	-0.43
FRP Waste Re-Use (virgin FRP credit)	-128.45	-7.29
FRP Waste Re-Use (SMC glass/filler credit)	-23.18	-1.72
FRP Waste in Thermolyzer (electricity credit)	-7.73	-0.43
FRP Waste in Thermolyzer (electricity & virgin fiber credit)	-84.87	-5.22

Techno-Economic Assessment (TEA) – Thermolyzer™

In addition to LCA, another important factor to drive the North American (NA) composites industry toward alternatives to landfilling and/or incineration of current and future composite EoL and manufacturing scrap streams (FRP recycle), is the economic attractiveness of the available options. Specifically, it is important to identify financially viable and economically sustainable solutions and strategies that provide the necessary incentives to drive the industry toward the goal of minimizing or eliminating FRP recycle streams routed to landfill and/or incineration (L/I).

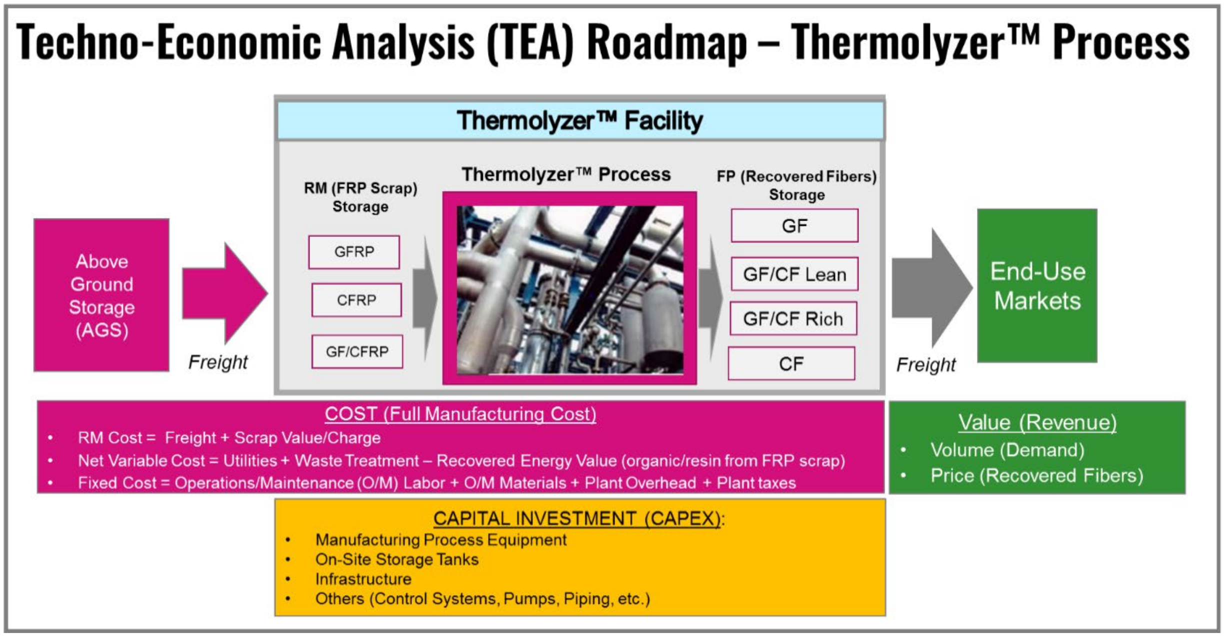
Key alternatives to L/I include: (1) recycling and/or (2) re-using these FRP recycle (scrap) streams to recover marketable/sellable recycled products and/or (3) capture the embodied energy from the organic materials (plastics/resins) contained in these scrap composite materials. The LCA benefits are attributed to: (1) displacing on-purpose products (produced via conventional manufacturing processes) with recycled/recovered materials, and (2) displacing conventional fuels (e.g., natural gas, oil, coal, etc.) with energy recovered from these recycled composites. The economic benefits include: (1) having a lower cost recycled versus on-purpose product available to the end users of composite materials and (2) reduced cost of energy recovered from the recycle streams versus conventional fuels. Fig. 15a provides a summary of the three different alternatives to L/I, along with the LCA and economic impact of each option, while Fig. 15b. illustrates the TEA roadmap for the Thermolyzer™ option.



	LCA Benefits or Impact					Economic Drivers or Impact		
	Transport (AGS to Facility)	Avoid Landfill	Recover Energy	Displace on-Purpose Products	LCA Overall	Recycled Product to Sell	Recycle Product Value	Investment
Thermolyzer	-	+	+	+ (fiber)	+++	Yes	High	High
Re-Grind Re-Use	-	+	-	++ (FRP)	+++	Yes	Low	Low
Cement Kiln	-	+	+	N/A	+	No	None	None

	LCA Impact				
	Transport (from Source)	FRP Waste	Energy Used		LCA Overall
LandFill	-	-			- -
Incinerate	-	-	- -		- - -

Figure 15a. Summary of FRP recycle alternatives to L/I, along with the LCA and economic impact of each.



COST (Full Manufacturing Cost)
- RM Cost = Freight + Scrap Value/Charge
- Net Variable Cost = Utilities + Waste Treatment – Recovered Energy Value (organic/resin from FRP scrap)
- Fixed Cost = Operations/Maintenance (O/M) Labor + O/M Materials + Plant Overhead + Plant taxes

Value (Revenue)
- Volume (Demand)
- Price (Recovered Fibers)

CAPITAL INVESTMENT (CAPEX):
- Manufacturing Process Equipment
- On-Site Storage Tanks
- Infrastructure
- Others (Control Systems, Pumps, Piping, etc.)

Figure 15b. TEA Roadmap for the Thermolyzer™ Process Option

To drive the North American (NA) composite industry to adopt alternative options to L/I for the FRP recycle streams, the following strategies are proposed

- **Above ground staging (AGS)** - Install or leverage existing infrastructure/assets at existing L/I facilities
    - Consolidate FRP recycle streams to optimize logistics to L/I alternatives (e.g., above ground storage within 200 miles allows one-day delivery)
    - Maintain supply of FRP raw material (**RM**) streams to mitigate impact on

    - Operational uptime – Thermolyzer^{TM} & Re-grind/Re-use
    - Process – Mainly cement kiln
    - Demand for end-use applications - Thermolyzer^{TM} & re-grind/re-use
  - Minimize variability of FRP RM streams to mitigate impact on
    - Process – Cement Kiln, Thermolyzer^{TM} and Re-grind/Re-use
    - Recycled Finished Product (FP) consistency - Thermolyzer^{TM} & Re-grind/Re-use
  - Minimize variability (amount/type of resin)
- **Pursue all L/I alternatives in parallel** – Allows quick adoption as higher value options are developed
  - **Cement kiln** – Fastest alternative to L/I as markets are developed to drive demand for the recovered products to trigger the re-grind/re-use and/or Thermolyzer^{TM} options (both options yield financial benefits by selling recovered products)
    - Cement kiln does not yield product to sell, so the key LCA benefit is recoverable energy
    - Can only consume GF recycle materials, which would account for the majority (~90%) of all FRP EoL and manufacturing scrap
      - **RM** consistency is important
      - Process is not compatible with CF or GF/CF hybrids
  - **Re-Grind/Re-Use** – Requires end-use market development and pull-through for the recovered <u>composite</u> products (GF, CF and/or GF/CF hybrids)
    - LCA benefits – Avoid L/I and displacing "on-purpose" (produced through conventional means) with "recycled" composite products
    - Financial benefits – Marginal value of "recycled" composites above cost
    - Can accept all FRP recycle streams (GF, CF and GF/CF hybrid), but supply and consistency are important to sell recovered composite products
  - **Thermolyzer™** – Also requires end-use market development and pull-through for the recovered <u>fiber</u> products (GF, CF and GF/CF hybrids)
    - LCA benefits – Avoid L/I, energy recovery from organics (resins), and displacing "on-purpose" with "recycled" fiber products
    - Financial benefits – Marginal value of "recycled" fibers above cost, with favorable return on investment
    - Can accept all FRP recycle streams (GF, CF and GF/CF hybrids), but supply and consistency are important for process operation and to produce consistent recovered fibers
    - FPs are recovered GF, CF and/or GF/CF fibers, produced by oxygen-free thermolysis that allows for the conversion of the organics (contained plastics in FRP Recycle streams) to syngas (CH_4/CO that can used for energy generation) and sellable FP

Since the Thermolyzer™ would require the highest level of investment, versus the re-grind/re-use and the cement kiln (minimum to no incremental investment) options, the focus of the current TEA was to evaluate the economic and financial feasibility of a standalone investment for a commercial scale Thermolyzer™ process (Greenfield Investment) in a strategic location/region within the continental US (e.g., within 200 miles from above ground storage of the FRP recycle/scrap streams, which would correspond to Midwest shipping radii).

The economic viability and sustainable financial benefits are key factors in providing the necessary incentives for the NA composites industry to consider the Thermolyzer™ as a viable alternative to L/I, and other options (i.e., cement kiln and re-grind/re-use). As stated above (and shown in Fig. 15), of the three L/I alternatives, only the Thermolyzer™ and re-grind/re-use options yield sellable recycled products to capture additional value. However, the Thermolyzer™ option would yield more marketable finished products (recovered fibers with more end-use options versus re-grind/re-use products) to maximize market demand pull-through, with a higher marginal value (vs re-grind/re-use) to further improve profitability.

The TEA to evaluate the economic/financial feasibility of the Thermolyzer™ option was based on the design provided by CHZ. Specifically, the design was based on key learnings (i.e., mass and energy balance, processability, product quality, etc.) from pilot scale testing completed by CHZ (in Forst, Germany) using the four different FRP scrap streams (Table 11) which are representative of the key industry segments (automotive and wind) that would account for the major sources of these composite scrap materials. The mass and energy balance from the Thermolyzer™ Pilot testing for each of the four different FRP scrap steams is summarized in Table 11.

In addition to the various sources, these streams also vary in the type of fibers (GF, CF and GF/CF hybrids) and resins (mainly thermosets), which provide a good representation of the large variability in the FRP scrap streams to be processed in a typical commercial Thermolyzer™ operation. The impact on process and recovered fiber product variability can be mitigated by segregating and inventorying the different FRP scrap materials (at the above ground storage location and Thermolyzer™ facility) which allows for better management and control of the raw materials (RM) fed to the Thermolyzer™ operation. The TEA assumed such an approach, where the RM inputs were not only managed to minimize impact on process, but provided the flexibility to evaluate different recovered fiber products based on market need and value creation (GF, CF and CF/GF hybrids).

Table 11. Mass and energy balance from the Thermolyzer™ pilot scale testing by CHZ in Forst, Germany

	Composite Recycle (scrap) Stream (RM - Raw material)	**Est. RM Feed Split**	**Mass Balance**		**Energy Balance (MJ basis)**		
			FP Yield	**Waste (solid/liquid)**	**TE**	**EC**	**NE**
			kg RM/kg FP	*kg Waste/kg FP*	*MJ/kg FP*		
1	CF epoxy wind blade spar cap GE (70% solid content)	5%	1.43	0.010	3.93	(3.93)	-
2	GF/CF epoxy hybrid John Deere (70% solids content)	5%	1.43	0.010	3.93	(3.93)	-
3	GF polyester/ vinyl ester automotive CSP (60% solid content)	45%	1.67	0.010	3.37	(4.72)	(1.35)
4	GF epoxy balsa/PVC foam wind blade GE (50% solid content)	45%	2.00	0.010	2.81	(5.61)	(2.81)
	Total Combined Stream (per unit of FP, or recovered Fiber)	100%	**1.79**	**0.010**	**3.17**	**(5.04)**	**(1.87)**
	Total Combined Stream (per unit of RM, or composite scrap)			**0.006**	**1.77**	**(2.81)**	**(1.04)**

FP - Finished Product (i.e., recovered Fibers from Thermolyzer)
RM - Raw Material (Shreded Recycle Composite fed to Thermolyzer)
TE - Total Energy to Convert RM to FP
EC - Energy Credit from organics - Recoverable Energy
NE - Net Energy - Zero/Negative - Energy neutral/Net energy producer

The key factors that are critical to driving the economic viability and financial sustainability of the Thermolyzer™ operation are as follows

1. Demand (volume) for recovered fibers (GF, CF and CF/GF hybrid) to fill capacity.
    - End-use markets need to be developed
    - Need market pull-through to drive growth
    - Establish sustainable demand
2. Market value for recovered fibers to support investment
    - Needs to be competitive on market value/performance versus "on-purpose" fibers
    - May require different fiber mix (e.g., GF, CF or GF/CF hybrid) to support pricing

3. Cost to produce recovered fibers to support a self-sustaining business model
    - Supply of FRP RM Recycle stream in freight logical location (within 200 miles)
    - Conversion cost (variable and fixed) to support pricing and/or margins to drive financial profitability (sustainability)
    - Energy recovered from the organics (resins) in FRP scrap streams supports the operation of the Thermolyzer™, while generating excess energy available to convert to electricity (see energy balance in Table 11)
4. Capital Investment – Is the demand and margin from selling recovered fibers sufficient to support/justify investment decision for at Thermolyzer™? Key factors include
    - Capital intensity (CI = Investment/capacity) – high CI at lower capacity requires higher margins to recover investment.
    - Greenfield (stand-alone) vs brownfield (add on to existing infrastructure/assets) investment
    - Is government (federal, state or local) or non-government organization (NGO) subsidy necessary to drive investment decision? To drive continued sustainable investment in the Thermolyzer™ operation (or other L/I alternatives), it is important to demonstrate economically viable options (using TEA) which are not dependent on subsidies.

Each of the above factors (key drivers #1 to 4) were evaluated to determine the economic viability and financial attractiveness of the Thermolyzer™ investment option. The different scenarios, assumptions and financial benefits/impact are summarized in Table 12.

Table 12. Financial summary of the Thermolyzer™ investment option with different recovered sellable product mix (GF, CF/GF Hybrid and CF)

Scenario		**Finished Product (FP)** *(GF, GF/CF, CF)*	**Market Value**$^{(1)}$	**Demand (5YRS)**	**Capacity**$^{(2)}$	**Invest** $^{(3)}$	**Financial Summary (WACC = 6%) (un-subsidized)**				
LCP - Long CF Price *MCP - Milled CF Price*		*% wt /% wt*	*$/kg*	*kta FP*	*kta FP*	*$mm*	*NPV6 ($mm)*	*CF* $^{(4)}$ *5YRS ($mm/yr)*	*XIRR (%)*	*Payback (YRS)*	*ROCC* $^{(5)}$ *(%)*
1	GF only	GF - 100	GF = 0.6	63	67	57	50	18	25%	4.7	13%
2a	CF Lean - LCP	CF/GF - 8/92	CF/GF = 1.8 (CF= 16.0/GF = 0.6)	63	67	57	384	70	97%	2.0	84%
2b	CF Lean - MCP	CF/GF - 8/92	CF/GF = 1.2 (CF = 8.0/GF = 0.6)	63	67	57	211	43	64%	2.7	50%
3a	CF rich - LCP	CF/GF - 30/70	CF/GF = 5.2 (CF = 16.0/GF = 0.6)	16	17	18	313	52	198%	1.1	171%
3b	CF rich - MCP	CF/GF - 30/70	CF/GF = 2.8 (CF = 8.0/GF = 0.6)	16	17	18	150	27	108%	1.8	98%
4a	CF only - LCP	CF - 100	CF = 16.0	9	17	18	616	100	415%	0.7	261%
4b	CF only - MCP	CF - 100	CF = 8.0	9	17	18	290	49	184%	1.2	163%

(1) Market Value - Takes into account possible loss in performance of recovered Fibers from "Thermolyzer" vs "on-purpose" fibers produced through conventional routes. CF Price assumptions - $16/kg long fiber (1 inch) and $8.0/kg milled fiber

(2) Capacity - FRP recycle or Raw Material (RM) and Recovered Fiber or Finished Product (FP).
FP from RM capacity based on CHZ mass balance from the four different products tested on pilot line

(3) Investment - Greenfield Investment (Thermolyzer™ Process and required infrastructure)

(4) CF - Cash Flow

(5) ROCC - Return on Capital Consumed (5 YR avg)

The key focus of the TEA was to evaluate possible commercial scenarios for the following types of recovered fiber products based on current view of market value for the recovered fibers and potential for demand pull-through using estimated volume projections at range of recovered fiber values.

1. GF only = 100% Glass
2. CF lean= 8/92 CF/GF hybrid
3. CF rich = 30/70 CF/GF hybrid
4. CF only = 100% Carbon

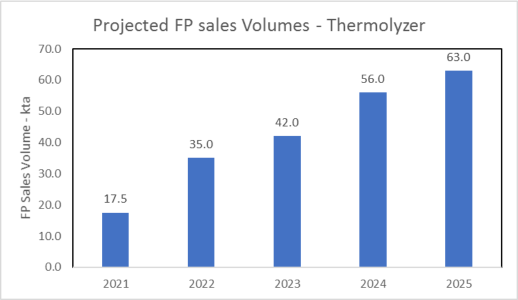
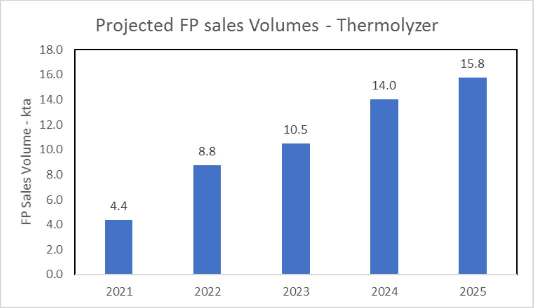
The market value for these recovered fibers were estimated using value-in-use for a given end-use application (cost to value), which were also discounted versus the "on-purpose" GF, CF (and CF/GF hybrid) alternatives to account for inferior performance associated with recovered products (e.g., degradation of sizing, higher variability in fiber length, reduced fiber length, etc.). For the recovered GF valued at \$0.6/kg (30-50% discount versus the "on-purpose" GF) was assumed, while the assumed value for CF were as follows.

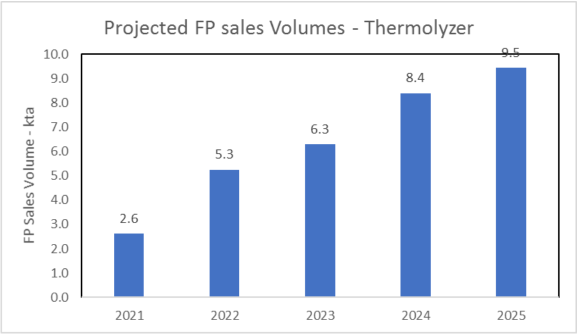
- Long carbon fiber (LCF, 1 inch fiber length market value of \$16/kg
- Milled carbon fiber (MCF, 1/16 inch fiber length market value of \$8.0/kg

For the CF lean/rich hybrids, assumed a weighted average market value using the above GF and CF estimates.

Although value will impact volume, to simplify our TEA assessment, the projected demand for the "GF only" (scenario 1) and "CF lean hybrid" (scenario 2a and 2b) products were assumed to be comparable, while the demand for the higher cost "CF rich hybrid" (scenario 3a and 3b) and "CF only" (scenario 4a and 4b) fibers were assumed to be about 4X and 6X lower, respectively. The capacities and demand projections for the different recovered fiber products are summarized in Table 13. As mentioned above, the capital intensity (investment/capacity) is higher for the lower capacity Thermolyzer™ investment, requiring higher net value to recover the initial investment.

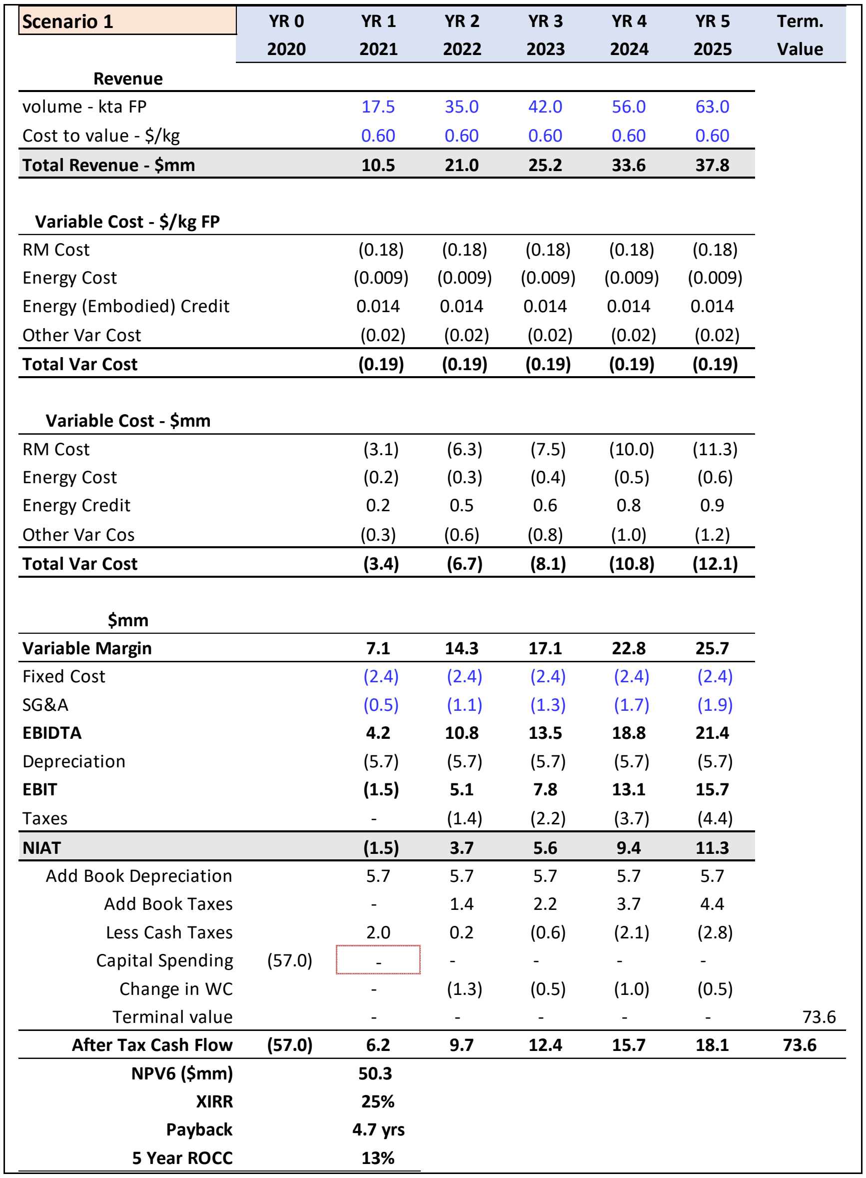
Table 13. Demand projections for by recovered fiber product (GF, CF lean, CF rich and CF)

Scenarios		Demand Projections
1, 2a & 2b	• Demand (5yr) = 63 kta FP • Capacity = 120 kta RM/67 kta FP • Investment = \$57 mm • Capital Intensity = \$0.85/kg FP (57/67)	
3a & 3b	• Demand (5yr) = 16 kta FP • Capacity = 30 kta RM/17 kta FP • Investment = \$18 mm • Capital Intensity = \$1.1/kg FP (18/17)	

4a & 4b	- Demand (5yr) = 10 kta FP - Capacity = 30 kta RM/17 kta FP - Investment = $18 mm - Capital Intensity = $1.1/kg FP (18/17)	

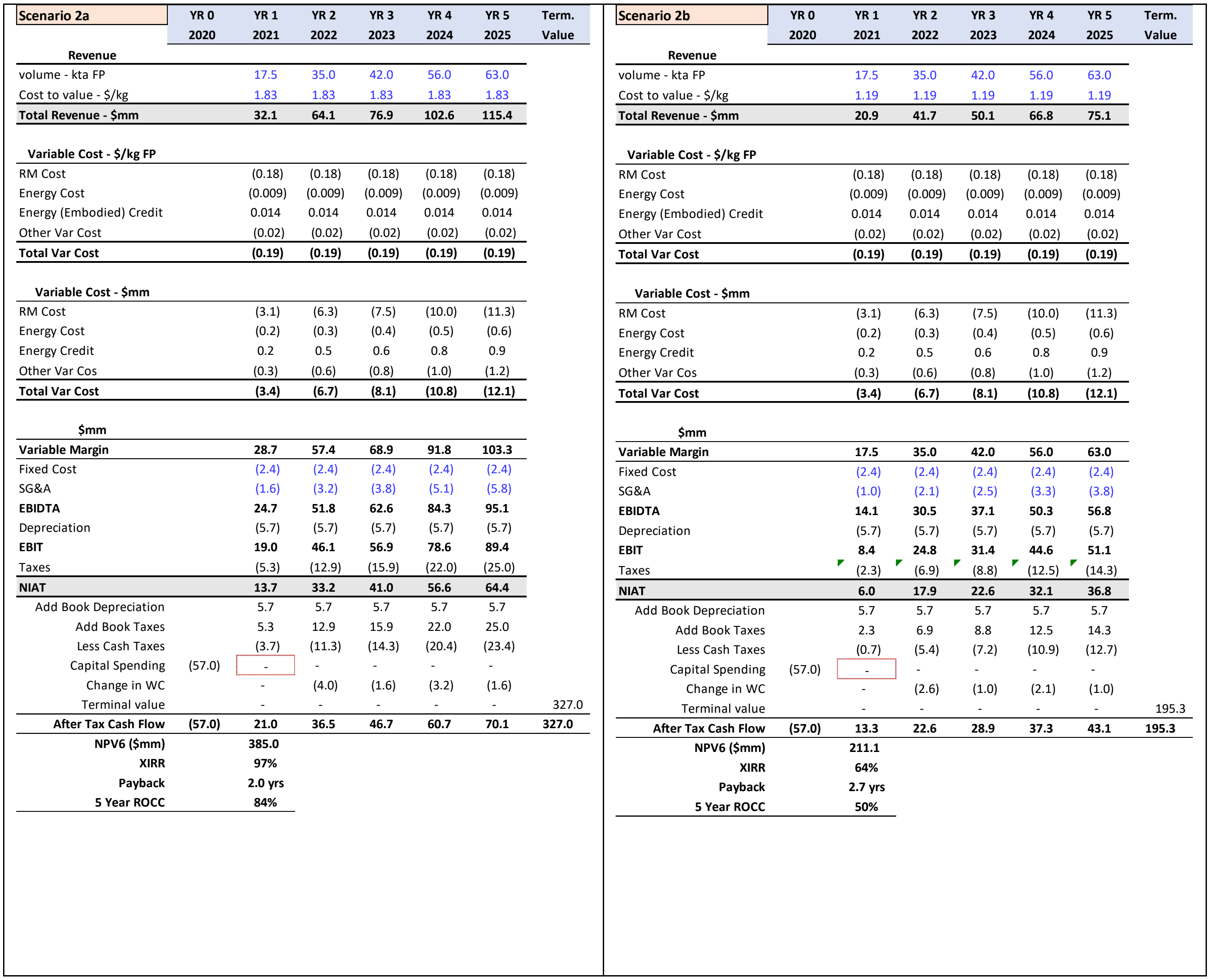
The manufacturing cost is mainly impacted by cost to ship FRP scrap to the Thermolyzer™ facility (assumed above ground storage within 200 miles, typical for the Midwest shipping corridor) and fixed cost (mostly in the early years, when there are lower volumes/margins to recover fixed cost). These, and other the other costs required to operate the Thermolyzer™ for each of the scenarios are shown in the 5 YR profit and loss (P&L) or cash flow (CF) summaries depicted in Tables 13-16.

Table 14. P&L for GF only scenario 1



Scenario 1	YR 0	YR 1	YR 2	YR 3	YR 4	YR 5	Term.
	2020	2021	2022	2023	2024	2025	Value
Revenue							
volume - kta FP		17.5	35.0	42.0	56.0	63.0	
Cost to value - $/kg		0.60	0.60	0.60	0.60	0.60	
Total Revenue - $mm		**10.5**	**21.0**	**25.2**	**33.6**	**37.8**	
Variable Cost - $/kg FP							
RM Cost		(0.18)	(0.18)	(0.18)	(0.18)	(0.18)	
Energy Cost		(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	
Energy (Embodied) Credit		0.014	0.014	0.014	0.014	0.014	
Other Var Cost		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	
Total Var Cost		**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	
Variable Cost - $mm							
RM Cost		(3.1)	(6.3)	(7.5)	(10.0)	(11.3)	
Energy Cost		(0.2)	(0.3)	(0.4)	(0.5)	(0.6)	
Energy Credit		0.2	0.5	0.6	0.8	0.9	
Other Var Cos		(0.3)	(0.6)	(0.8)	(1.0)	(1.2)	
Total Var Cost		**(3.4)**	**(6.7)**	**(8.1)**	**(10.8)**	**(12.1)**	
$mm							
Variable Margin		**7.1**	**14.3**	**17.1**	**22.8**	**25.7**	
Fixed Cost		(2.4)	(2.4)	(2.4)	(2.4)	(2.4)	
SG&A		(0.5)	(1.1)	(1.3)	(1.7)	(1.9)	
EBIDTA		**4.2**	**10.8**	**13.5**	**18.8**	**21.4**	
Depreciation		(5.7)	(5.7)	(5.7)	(5.7)	(5.7)	
EBIT		**(1.5)**	**5.1**	**7.8**	**13.1**	**15.7**	
Taxes		-	(1.4)	(2.2)	(3.7)	(4.4)	
NIAT		**(1.5)**	**3.7**	**5.6**	**9.4**	**11.3**	
Add Book Depreciation		5.7	5.7	5.7	5.7	5.7	
Add Book Taxes		-	1.4	2.2	3.7	4.4	
Less Cash Taxes		2.0	0.2	(0.6)	(2.1)	(2.8)	
Capital Spending	(57.0)	-	-	-	-	-	
Change in WC		-	(1.3)	(0.5)	(1.0)	(0.5)	
Terminal value		-	-	-	-	-	73.6
After Tax Cash Flow	**(57.0)**	**6.2**	**9.7**	**12.4**	**15.7**	**18.1**	**73.6**
NPV6 ($mm)		**50.3**					
XIRR		**25%**					
Payback		**4.7 yrs**					
5 Year ROCC		**13%**					

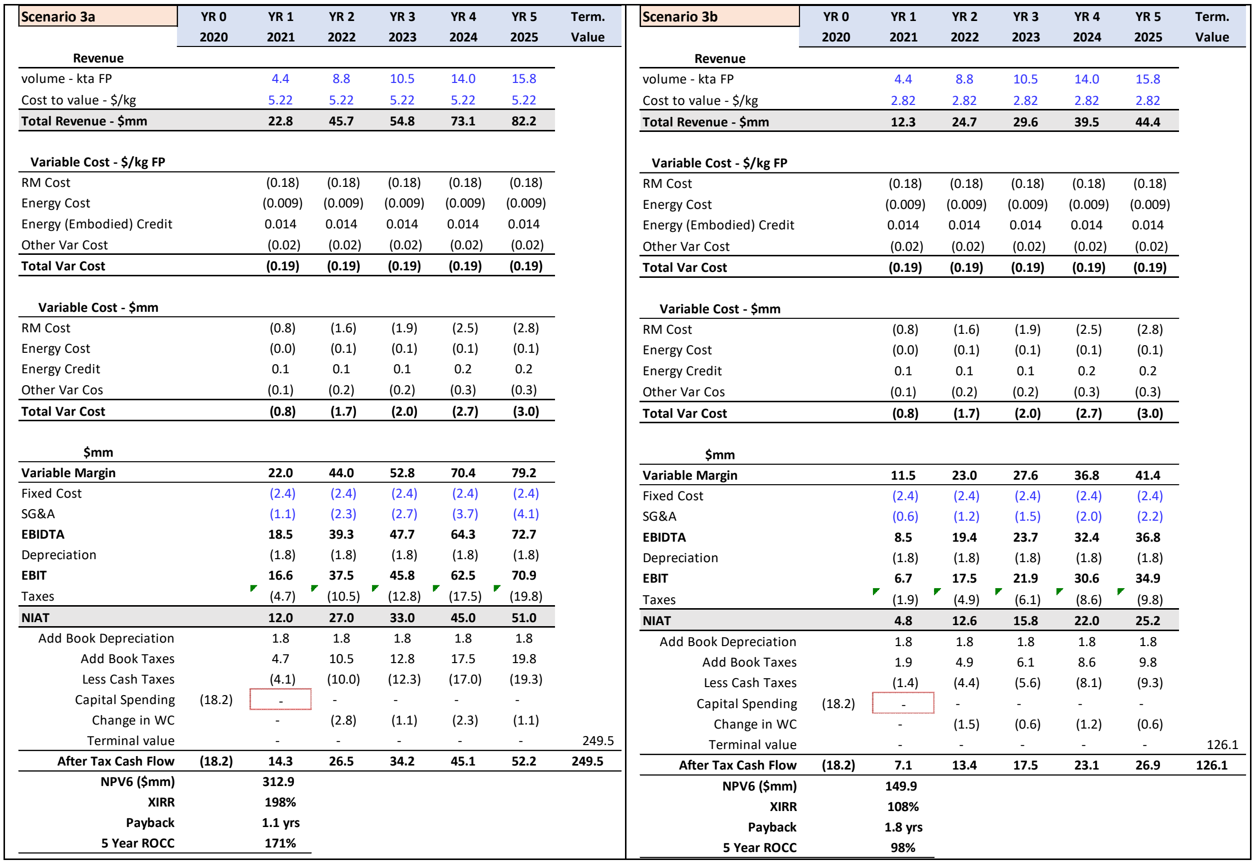
Table 15. P&L for CF lean CF/GF scenarios 2a and 2b



Scenario 2a	**YR 0** **2020**	**YR 1** **2021**	**YR 2** **2022**	**YR 3** **2023**	**YR 4** **2024**	**YR 5** **2025**	**Term.** **Value**
Revenue							
volume - kta FP		17.5	35.0	42.0	56.0	63.0	
Cost to value - $/kg		1.83	1.83	1.83	1.83	1.83	
Total Revenue - $mm		**32.1**	**64.1**	**76.9**	**102.6**	**115.4**	
Variable Cost - $/kg FP							
RM Cost		(0.18)	(0.18)	(0.18)	(0.18)	(0.18)	
Energy Cost		(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	
Energy (Embodied) Credit		0.014	0.014	0.014	0.014	0.014	
Other Var Cost		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	
Total Var Cost		**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	
Variable Cost - $mm							
RM Cost		(3.1)	(6.3)	(7.5)	(10.0)	(11.3)	
Energy Cost		(0.2)	(0.3)	(0.4)	(0.5)	(0.6)	
Energy Credit		0.2	0.5	0.6	0.8	0.9	
Other Var Cos		(0.3)	(0.6)	(0.8)	(1.0)	(1.2)	
Total Var Cost		**(3.4)**	**(6.7)**	**(8.1)**	**(10.8)**	**(12.1)**	
$mm							
Variable Margin		**28.7**	**57.4**	**68.9**	**91.8**	**103.3**	
Fixed Cost		(2.4)	(2.4)	(2.4)	(2.4)	(2.4)	
SG&A		(1.6)	(3.2)	(3.8)	(5.1)	(5.8)	
EBIDTA		**24.7**	**51.8**	**62.6**	**84.3**	**95.1**	
Depreciation		(5.7)	(5.7)	(5.7)	(5.7)	(5.7)	
EBIT		**19.0**	**46.1**	**56.9**	**78.6**	**89.4**	
Taxes		(5.3)	(12.9)	(15.9)	(22.0)	(25.0)	
NIAT		**13.7**	**33.2**	**41.0**	**56.6**	**64.4**	
Add Book Depreciation		5.7	5.7	5.7	5.7	5.7	
Add Book Taxes		5.3	12.9	15.9	22.0	25.0	
Less Cash Taxes		(3.7)	(11.3)	(14.3)	(20.4)	(23.4)	
Capital Spending	(57.0)	-	-	-	-	-	
Change in WC		-	(4.0)	(1.6)	(3.2)	(1.6)	
Terminal value		-	-	-	-	-	327.0
After Tax Cash Flow	**(57.0)**	**21.0**	**36.5**	**46.7**	**60.7**	**70.1**	**327.0**
NPV6 ($mm)		**385.0**					
XIRR		**97%**					
Payback		**2.0 yrs**					
5 Year ROCC		**84%**					

Scenario 2b	**YR 0** **2020**	**YR 1** **2021**	**YR 2** **2022**	**YR 3** **2023**	**YR 4** **2024**	**YR 5** **2025**	**Term.** **Value**
Revenue							
volume - kta FP		17.5	35.0	42.0	56.0	63.0	
Cost to value - $/kg		1.19	1.19	1.19	1.19	1.19	
Total Revenue - $mm		**20.9**	**41.7**	**50.1**	**66.8**	**75.1**	
Variable Cost - $/kg FP							
RM Cost		(0.18)	(0.18)	(0.18)	(0.18)	(0.18)	
Energy Cost		(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	
Energy (Embodied) Credit		0.014	0.014	0.014	0.014	0.014	
Other Var Cost		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	
Total Var Cost		**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	
Variable Cost - $mm							
RM Cost		(3.1)	(6.3)	(7.5)	(10.0)	(11.3)	
Energy Cost		(0.2)	(0.3)	(0.4)	(0.5)	(0.6)	
Energy Credit		0.2	0.5	0.6	0.8	0.9	
Other Var Cos		(0.3)	(0.6)	(0.8)	(1.0)	(1.2)	
Total Var Cost		**(3.4)**	**(6.7)**	**(8.1)**	**(10.8)**	**(12.1)**	
$mm							
Variable Margin		**17.5**	**35.0**	**42.0**	**56.0**	**63.0**	
Fixed Cost		(2.4)	(2.4)	(2.4)	(2.4)	(2.4)	
SG&A		(1.0)	(2.1)	(2.5)	(3.3)	(3.8)	
EBIDTA		**14.1**	**30.5**	**37.1**	**50.3**	**56.8**	
Depreciation		(5.7)	(5.7)	(5.7)	(5.7)	(5.7)	
EBIT		**8.4**	**24.8**	**31.4**	**44.6**	**51.1**	
Taxes		(2.3)	(6.9)	(8.8)	(12.5)	(14.3)	
NIAT		**6.0**	**17.9**	**22.6**	**32.1**	**36.8**	
Add Book Depreciation		5.7	5.7	5.7	5.7	5.7	
Add Book Taxes		2.3	6.9	8.8	12.5	14.3	
Less Cash Taxes		(0.7)	(5.4)	(7.2)	(10.9)	(12.7)	
Capital Spending	(57.0)	-	-	-	-	-	
Change in WC		-	(2.6)	(1.0)	(2.1)	(1.0)	
Terminal value		-	-	-	-	-	195.3
After Tax Cash Flow	**(57.0)**	**13.3**	**22.6**	**28.9**	**37.3**	**43.1**	**195.3**
NPV6 ($mm)		**211.1**					
XIRR		**64%**					
Payback		**2.7 yrs**					
5 Year ROCC		**50%**					

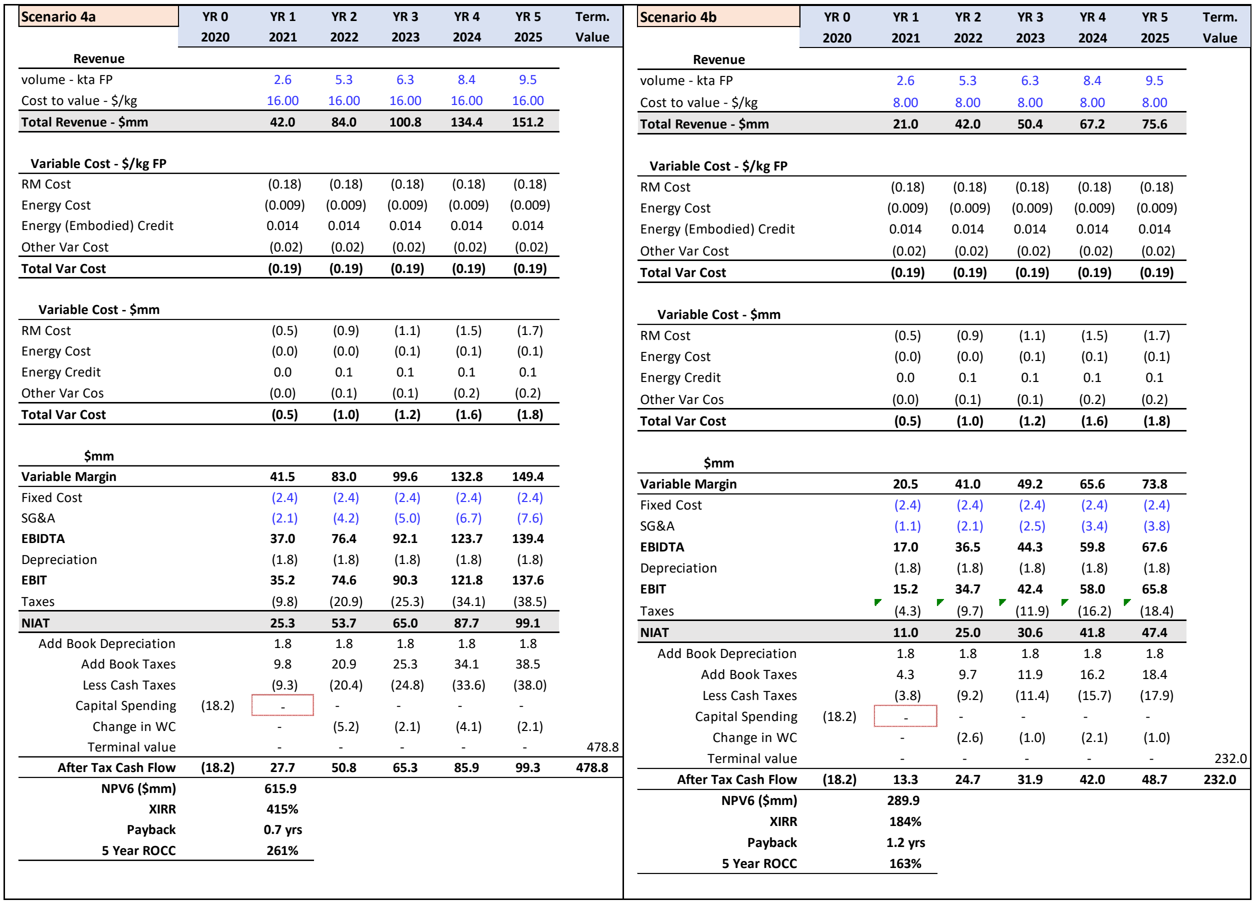
Table 16. P&L for CF rich CF/GF scenarios 3a and 3b



Scenario 3a	YR 0 2020	YR 1 2021	YR 2 2022	YR 3 2023	YR 4 2024	YR 5 2025	Term. Value
Revenue							
volume - kta FP		4.4	8.8	10.5	14.0	15.8	
Cost to value - $/kg		5.22	5.22	5.22	5.22	5.22	
Total Revenue - $mm		**22.8**	**45.7**	**54.8**	**73.1**	**82.2**	
Variable Cost - $/kg FP							
RM Cost		(0.18)	(0.18)	(0.18)	(0.18)	(0.18)	
Energy Cost		(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	
Energy (Embodied) Credit		0.014	0.014	0.014	0.014	0.014	
Other Var Cost		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	
Total Var Cost		**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	
Variable Cost - $mm							
RM Cost		(0.8)	(1.6)	(1.9)	(2.5)	(2.8)	
Energy Cost		(0.0)	(0.1)	(0.1)	(0.1)	(0.1)	
Energy Credit		0.1	0.1	0.1	0.2	0.2	
Other Var Cos		(0.1)	(0.2)	(0.2)	(0.3)	(0.3)	
Total Var Cost		**(0.8)**	**(1.7)**	**(2.0)**	**(2.7)**	**(3.0)**	
$mm							
Variable Margin		**22.0**	**44.0**	**52.8**	**70.4**	**79.2**	
Fixed Cost		(2.4)	(2.4)	(2.4)	(2.4)	(2.4)	
SG&A		(1.1)	(2.3)	(2.7)	(3.7)	(4.1)	
EBIDTA		**18.5**	**39.3**	**47.7**	**64.3**	**72.7**	
Depreciation		(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	
EBIT		**16.6**	**37.5**	**45.8**	**62.5**	**70.9**	
Taxes		(4.7)	(10.5)	(12.8)	(17.5)	(19.8)	
NIAT		**12.0**	**27.0**	**33.0**	**45.0**	**51.0**	
Add Book Depreciation		1.8	1.8	1.8	1.8	1.8	
Add Book Taxes		4.7	10.5	12.8	17.5	19.8	
Less Cash Taxes		(4.1)	(10.0)	(12.3)	(17.0)	(19.3)	
Capital Spending	(18.2)	-	-	-	-	-	
Change in WC		-	(2.8)	(1.1)	(2.3)	(1.1)	
Terminal value		-	-	-	-	-	249.5
After Tax Cash Flow	**(18.2)**	**14.3**	**26.5**	**34.2**	**45.1**	**52.2**	**249.5**
NPV6 ($mm)		**312.9**					
XIRR		**198%**					
Payback		**1.1 yrs**					
5 Year ROCC		**171%**					

Scenario 3b	YR 0 2020	YR 1 2021	YR 2 2022	YR 3 2023	YR 4 2024	YR 5 2025	Term. Value
Revenue							
volume - kta FP		4.4	8.8	10.5	14.0	15.8	
Cost to value - $/kg		2.82	2.82	2.82	2.82	2.82	
Total Revenue - $mm		**12.3**	**24.7**	**29.6**	**39.5**	**44.4**	
Variable Cost - $/kg FP							
RM Cost		(0.18)	(0.18)	(0.18)	(0.18)	(0.18)	
Energy Cost		(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	
Energy (Embodied) Credit		0.014	0.014	0.014	0.014	0.014	
Other Var Cost		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	
Total Var Cost		**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	
Variable Cost - $mm							
RM Cost		(0.8)	(1.6)	(1.9)	(2.5)	(2.8)	
Energy Cost		(0.0)	(0.1)	(0.1)	(0.1)	(0.1)	
Energy Credit		0.1	0.1	0.1	0.2	0.2	
Other Var Cos		(0.1)	(0.2)	(0.2)	(0.3)	(0.3)	
Total Var Cost		**(0.8)**	**(1.7)**	**(2.0)**	**(2.7)**	**(3.0)**	
$mm							
Variable Margin		**11.5**	**23.0**	**27.6**	**36.8**	**41.4**	
Fixed Cost		(2.4)	(2.4)	(2.4)	(2.4)	(2.4)	
SG&A		(0.6)	(1.2)	(1.5)	(2.0)	(2.2)	
EBIDTA		**8.5**	**19.4**	**23.7**	**32.4**	**36.8**	
Depreciation		(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	
EBIT		**6.7**	**17.5**	**21.9**	**30.6**	**34.9**	
Taxes		(1.9)	(4.9)	(6.1)	(8.6)	(9.8)	
NIAT		**4.8**	**12.6**	**15.8**	**22.0**	**25.2**	
Add Book Depreciation		1.8	1.8	1.8	1.8	1.8	
Add Book Taxes		1.9	4.9	6.1	8.6	9.8	
Less Cash Taxes		(1.4)	(4.4)	(5.6)	(8.1)	(9.3)	
Capital Spending	(18.2)	-	-	-	-	-	
Change in WC		-	(1.5)	(0.6)	(1.2)	(0.6)	
Terminal value		-	-	-	-	-	126.1
After Tax Cash Flow	**(18.2)**	**7.1**	**13.4**	**17.5**	**23.1**	**26.9**	**126.1**
NPV6 ($mm)		**149.9**					
XIRR		**108%**					
Payback		**1.8 yrs**					
5 Year ROCC		**98%**					

Table 17. P&L for CF only scenarios 4a and 4b



Scenario 4a	**YR 0** **2020**	**YR 1** **2021**	**YR 2** **2022**	**YR 3** **2023**	**YR 4** **2024**	**YR 5** **2025**	**Term.** **Value**
Revenue							
volume - kta FP		2.6	5.3	6.3	8.4	9.5	
Cost to value - $/kg		16.00	16.00	16.00	16.00	16.00	
Total Revenue - $mm		**42.0**	**84.0**	**100.8**	**134.4**	**151.2**	
Variable Cost - $/kg FP							
RM Cost		(0.18)	(0.18)	(0.18)	(0.18)	(0.18)	
Energy Cost		(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	
Energy (Embodied) Credit		0.014	0.014	0.014	0.014	0.014	
Other Var Cost		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	
Total Var Cost		**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	
Variable Cost - $mm							
RM Cost		(0.5)	(0.9)	(1.1)	(1.5)	(1.7)	
Energy Cost		(0.0)	(0.0)	(0.1)	(0.1)	(0.1)	
Energy Credit		0.0	0.1	0.1	0.1	0.1	
Other Var Cos		(0.0)	(0.1)	(0.1)	(0.2)	(0.2)	
Total Var Cost		**(0.5)**	**(1.0)**	**(1.2)**	**(1.6)**	**(1.8)**	
$mm							
Variable Margin		**41.5**	**83.0**	**99.6**	**132.8**	**149.4**	
Fixed Cost		(2.4)	(2.4)	(2.4)	(2.4)	(2.4)	
SG&A		(2.1)	(4.2)	(5.0)	(6.7)	(7.6)	
EBIDTA		**37.0**	**76.4**	**92.1**	**123.7**	**139.4**	
Depreciation		(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	
EBIT		**35.2**	**74.6**	**90.3**	**121.8**	**137.6**	
Taxes		(9.8)	(20.9)	(25.3)	(34.1)	(38.5)	
NIAT		**25.3**	**53.7**	**65.0**	**87.7**	**99.1**	
Add Book Depreciation		1.8	1.8	1.8	1.8	1.8	
Add Book Taxes		9.8	20.9	25.3	34.1	38.5	
Less Cash Taxes		(9.3)	(20.4)	(24.8)	(33.6)	(38.0)	
Capital Spending	(18.2)	-	-	-	-	-	
Change in WC		-	(5.2)	(2.1)	(4.1)	(2.1)	
Terminal value		-	-	-	-	-	478.8
After Tax Cash Flow	**(18.2)**	**27.7**	**50.8**	**65.3**	**85.9**	**99.3**	**478.8**
NPV6 ($mm)		**615.9**					
XIRR		**415%**					
Payback		**0.7 yrs**					
5 Year ROCC		**261%**					

Scenario 4b	**YR 0** **2020**	**YR 1** **2021**	**YR 2** **2022**	**YR 3** **2023**	**YR 4** **2024**	**YR 5** **2025**	**Term.** **Value**
Revenue							
volume - kta FP		2.6	5.3	6.3	8.4	9.5	
Cost to value - $/kg		8.00	8.00	8.00	8.00	8.00	
Total Revenue - $mm		**21.0**	**42.0**	**50.4**	**67.2**	**75.6**	
Variable Cost - $/kg FP							
RM Cost		(0.18)	(0.18)	(0.18)	(0.18)	(0.18)	
Energy Cost		(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	
Energy (Embodied) Credit		0.014	0.014	0.014	0.014	0.014	
Other Var Cost		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	
Total Var Cost		**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	**(0.19)**	
Variable Cost - $mm							
RM Cost		(0.5)	(0.9)	(1.1)	(1.5)	(1.7)	
Energy Cost		(0.0)	(0.0)	(0.1)	(0.1)	(0.1)	
Energy Credit		0.0	0.1	0.1	0.1	0.1	
Other Var Cos		(0.0)	(0.1)	(0.1)	(0.2)	(0.2)	
Total Var Cost		**(0.5)**	**(1.0)**	**(1.2)**	**(1.6)**	**(1.8)**	
$mm							
Variable Margin		**20.5**	**41.0**	**49.2**	**65.6**	**73.8**	
Fixed Cost		(2.4)	(2.4)	(2.4)	(2.4)	(2.4)	
SG&A		(1.1)	(2.1)	(2.5)	(3.4)	(3.8)	
EBIDTA		**17.0**	**36.5**	**44.3**	**59.8**	**67.6**	
Depreciation		(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	
EBIT		**15.2**	**34.7**	**42.4**	**58.0**	**65.8**	
Taxes		(4.3)	(9.7)	(11.9)	(16.2)	(18.4)	
NIAT		**11.0**	**25.0**	**30.6**	**41.8**	**47.4**	
Add Book Depreciation		1.8	1.8	1.8	1.8	1.8	
Add Book Taxes		4.3	9.7	11.9	16.2	18.4	
Less Cash Taxes		(3.8)	(9.2)	(11.4)	(15.7)	(17.9)	
Capital Spending	(18.2)	-	-	-	-	-	
Change in WC		-	(2.6)	(1.0)	(2.1)	(1.0)	
Terminal value		-	-	-	-	-	232.0
After Tax Cash Flow	**(18.2)**	**13.3**	**24.7**	**31.9**	**42.0**	**48.7**	**232.0**
NPV6 ($mm)		**289.9**					
XIRR		**184%**					
Payback		**1.2 yrs**					
5 Year ROCC		**163%**					

In addition to the market value for recovered materials, volume and cost, the other key driver evaluated was the impact of government and/or NGO subsidy on the payback period to recover the initial Thermolyzer™ investment.

The financial benefits for each of the "non-subsidized" and "subsidized" scenarios are summarized in Table 18. Although the economic attractiveness will depend on the alternative value for the investors capital deployment (return on alternative investment options), other than the long payback (4.7 years) for the GF only option, all scenarios have a less than 2.7 years payback, with attractive financial returns as shown in Table 12 (i.e., NPV, XIRR, ROCC and CF).

Although the financial returns for all scenarios would be sufficient (especially all CF/GF Hybrid and CF only scenarios) to provide the necessary incentive for investment without subsidy, with some government and/or NGO subsidies, the attractiveness of some of the scenarios with less favorable payback could be enhanced. This could be a viable strategy for early adopters who are trying to weigh the risk of investment against the risk of having sufficient demand pull-through to achieve acceptable financial returns. The impact of different levels of subsidies on the investment payback is shown in Table 18.

Table 18. Impact of different subsidy on payback

		% of Investment Subsidized			
		none	25%	50%	75%
Scenario		Payback (yrs)			
1	GF only	**4.7**	**4.1**	**3.4**	**2.3**
2a	CF Lean - LCP	**2.0**	**1.6**	**1.3**	**0.8**
2b	CF Lean - MCP	**2.7**	**2.3**	**1.8**	**1.2**
3a	CF rich - LCP	**1.1**	**1.0**	**0.7**	**0.3**
3b	CF rich - MCP	**1.8**	**1.5**	**1.2**	**0.7**
4a	CF Only - LCP	**0.7**	**0.5**	**0.3**	**0.2**
4b	CF Only - MCP	**1.2**	**1.0**	**0.7**	**0.4**

However, it should be noted that the following key factors need to be considered (and further investigated) for the Thermolyzer™ and re-grind/re-use options (as shown in Table 9 LCA summary) to be an economically viable and financially sustainable alternative to L/I:

1. Demand – It is critical to identify and develop multiple end-use opportunities to drive adoption and accelerate market growth for recovered finished products (FP)
2. Sustainable supply and consistent quality of recovered FPs - To drive market adoption, it is important to develop strategy (and/or further validate above ground storage and staging strategy discussed earlier) to assure that end-users have sustainable supply of recovered products with the level of consistency to meet their needs
3. Market Value/Performance – Recovered FPs must provide sufficient market value as compared with "on-purpose" alternatives, while discounting for any loss in performance attributed to use of recovered FPs
4. Leverage existing Thermolyzer™ facilities/assets used to recycle other products (e.g., tire, carpet, plastics, etc.) – This could be an alternative (versus subsidies) option to reduce capital investment for a Thermolyzer™ to process FRP scrap (i.e., leveraging existing infrastructure)

5. BENEFITS ASSESSMENT

Inherent Energy is recovered from waste materials to operate the Thermolyzer™ system. Recovering that energy reduces the amount of non-renewable energy required to produce the same power. Plus, the Thermolyzer™ process keeps those materials from disposal in landfills. Mass-energy balance and TEA results indicate that the pyrolysis process can generate enough energy from the input waste materials to be self-sustaining and yield fiber with significantly less input energy than required for virgin fiber production.

Fiber Recovery is possible through the Thermolyzer™ process. Both glass and carbon fibers can be recovered from the Thermolyzer™ char. Successful reusability depends on the operating conditions of the Thermolyzer™ system which impact recycled fiber properties as well as market demand for recycled fibers. Successful recovery of usable fibers adds to the economics of the process and significantly reduced materials sent to a landfill

Avoidance of toxic by-products for composites containing halogenated flame retardants is a key criteria for any pyrolysis recycling solution. Thermolyzer^{TM} converts halogen acids formed in the primary reactor to form non-hazardous salts that can be removed and safely disposed.

Environmental permitting would be facilitated by the safe elimination of the acid gases, no detectable levels of dioxin/furans, low VOC in ambient air, water discharge quality, clean syngas and no noise. The test protocols from the test materials can be used for permit applications to meet State and Local Environmental requirements.

6. COMMERCIALIZATION

If proven to yield glass and carbon fiber of sufficient economic value with minimal energy costs and emissions issues, the Thermolyzer^{TM} technology is ready for rapid commercialization for composite processing. The results of the pilot test were encouraging, but more process development needs to be done. The following are the critical elements of the Commercialization Plan:

- **Strategic Partners**
    - Oak Ridge National Laboratories
    - University of Tennessee
    - ACMA/IACMI
    - A. Schulman, CSP, Owens-Corning, U. Maine, etc.
- **Current Project list**
    - CHZ is developing an SBIR proposal to continue this composite recycling development. In addition, we have a range of projects from behind-the-meter corporate, to community, to university and international customers. They are focused on using tires or plastics as feedstocks and appropriate byproducts.

7. ACCOMPLISHMENTS

Four samples of various composite materials containing both glass and carbon fibers were successfully processed in the Thermolyzer^{TM} system. The processed carbon fibers retained desired mechanical properties and appear potentially suitable for reuse, but more testing is required. The glass fibers showed a decrease in properties at the temperature of processing. This was expected and confirmed in post-testing at ORNL. A major finding was the need to modify the feed system of the Thermolyzer^{TM} to eliminate fiber shearing in the feed mechanisms and some design modifications to enhance dwell time and temperature control in the secondary reactor which ran high at 550°C. Lab scale experiments indicate running the process at a lower temperature 400-450°C would yield higher strength glass fibers and more energy efficient with the gas that is produced. Therefore, modification of the stock Thermolyzer^{TM} process settings should be capable of yielding glass fibers with mechanical properties suitable for reuse.

CHZ Technology, LLC Announces it is a Dual 2018 R&D 100 Winner

CHZ Technology's Thermolyzer^{TM} technology was recently recognized as one of the 100 most innovative technologies in 2018 by R&D Magazine.[10] CHZ's Thermolyzer™ Technology was not only one of the R&D 100 most innovative technology winners but it also received the R&D 100 "Special Recognition Bronze Award" for Green Technology.

Publications & Presentations:

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8. CONCLUSIONS

- The Thermolyzer^{TM} technology is capable of processing cured composite waste materials and recover the glass or carbon fiber from the polymer matrix.
- The recovered carbon fiber reinforcement can be tailored to perform in commercial composites.
- The recovered glass fibers need further Thermolyzer^{TM} process optimization for time at temperature.
- The Thermolyzer^{TM} system is designed to process a diverse range of EoL materials in the pilot unit located at KUG in Forst (Lausitz), Germany. However, the system must be modified to efficiently process the high load levels of the composite materials glass and carbon fibers efficiently. Process concerns include the conveyor feed system, primary reactor heating design and the secondary reactor design to minimize shear stress in the fibers and enhance the ability to "gently" process the delicate fibers.
- Recovered glass and carbon recycled fiber may be combinable to improve glass fiber feedstock mechanical properties and stretch comparatively limited carbon fiber supplies with an intermediate value product.
- The LCA shows that accounting for avoided grid electricity and avoided virgin fiber products in the business model allows the most significant effect on CED and TRACI for Thermolyzer^{TM} process.
- The economic impact confirms a mixed waste stream supports good payback on investment without requiring a subsidy for the Thermolyzer^{TM} process. The glass fiber is necessary for scale and ease of processing, while the carbon fiber adds more value to the performance in the final application.
- Above ground storage and staging strategy facilitates the economic viability and flexibility to optimize the business model to send GFRP to re-use applications, or GFRP shred to cement kiln, and/or hybrid GF/CF FRP or CFRP to ThermolyzerTM for fiber re-use
- Above ground storage also allows for quick implementation of L/I alternatives like the cement kiln, as markets are developed for recovered fiber from the Thermolyzer™ (and re-grind/re-use)

9. RECOMMENDATIONS

Detailed engineering studies need to be completed on the Thermolyzer^{TM} to enable the commercial production systems to successfully process EoL composites. The Thermolyzer^{TM} controlled pyrolysis process can be used for composites with high fiber loadings, but modifications are needed in the conveyor feed sections, the primary reactor to uniformly gasify the composite shreds, and the secondary reactors to increase the thermal dwell time yet minimize applied shear to the delicate fibers. These modifications would enable various composite feedstocks likely to be processed at a commercial Thermolyzer^{TM} installation. A 2nd pilot trial should be conducted to collect fiber more representative of a real recycling operation. Additional cleaning and purge procedures for the Thermolyzer^{TM} reactor will yield materials without significant foreign contaminants allowing more in-depth 2nd generation composite development.

The LCA and TEA will support in Phase 2:

(1) Confirmation of the potential noncontaminated yield of the Thermolyzer^{TM} process,

(2) Validation of the value of avoided products with closer examination of value proposition of the Thermolyzer^{TM}, and

(3) Validation that above ground storage and staging can better facilitate the economic viability of GFRP recovery processes such as cement kiln and the Thermolyzer^{TM}.

10 BIBLIOGRAPHY

[1] Thomason J, Jenkins P, Yang L. Glass Fibre Strength – A Review with Relation to Composite Recycling. Fibers 2016; 4(2):18.

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11. APPENDICES

Appendix A: Test protocol at the pilot plant in Forst, Germany

Appendix B: TEA Assumptions

Appendix A:
Test protocol at the pilot plant in Forst, Germany

Kunststoff- und Umwelttechnik GmbH
Waldstraße 14
03149 Forst (Lausitz), Germany

Date: 3-28-2018

Content

1 Subject of the test

The object of the test was to process different types of composite materials made with carbon and glass fibers in the pilot plant in Forst to determine the recovered fiber properties. In the time period from 3-8-2018 to 3-28-2018, the plant was operated in several operating phases with four types of material, which were specified and supplied by CHZ. The composition and structure of the material types differed significantly from the usual input materials, in particular, the glass fiber and carbon fiber content, which is an inert material for the thermolysis process. Due to the high fiber content of these composites they did not behave in the way that our other feed stocks have done. This behavior will be discussed later.

2 Target of the test procedure

The target of the test was to test carefully chosen operational settings of the plant, to determine technical functional effects when using the supplied composites, and, above all, to decompose the resins in the composites to obtain fibers for measuring their mechanical properties. The operating parameters of the system had to be determined and evaluated accordingly.

3 Summary of the results

- Tests with these four types of materials
    1. CF epoxy wind blade spar cap GE
    2. GF/CF epoxy hybrid John Deere
    3. GF polyester/ vinyl ester automotive CSP
    4. 4. GF epoxy balsa/PVC foam wind blade GE were carried out. In doing so, the above-mentioned and required objectives were achieved.
- The transport characteristics of the various materials were not typical for most bulk materials. However, the technology used in the process requires that the material behaves like a bulk material and falls by itself into a shaft at the end of a screw conveyor. In this respect, the transport screw mechanism was not fully optimized for conveying a felt-like body made of fibers. In the first reactor, this material is not completely gasified by design, then must be discharged into the secondary reactor. In this respect, the thermolysis process could be carried out as planned, because the thermolysis product could not be completely discharged. It had to be partially removed after the tests.
- This effect can be avoided in the future by changing the screw discharge design. Furthermore, it is possible to mix the composite materials with wood pellets and process them together in order to maintain the bulk material characteristic for better material transport within the system.
- The expected function of the plant regarding the gasification of the polymer matrix was demonstrated, as the transport problems encountered at specific locations in the equipment had no influence on the gasification performance.
- Partial quantities of the produced fiber types were sent to the customer for measurement of the fiber properties.

- Gas samples were taken from the generated gas and delivered to a certified laboratory for analysis. The analyses revealed a gas composition that met expectations and are presented later in this report.

  The gas has a composition suitable for gas usage with expected proportions of hydrogen, methane and carbon monoxide. The carbon dioxide content is partially higher due to the low reaction temperatures used to retain fiber properties.
- To prove that no dioxin formation occurs during the process, a sample for dioxin measurement was taken during the pilot operation with PVC material. The results confirm, as in previous tests, that no dioxins are formed.
- The quantities of solids used and produced were accounted for. The solids content of the composites was determined as follows:

1.	CF epoxy wind blade laminate	ca. 70 %
2.	GF/CF epoxy hybrid John Deere	ca. 70 %
3.	GF polyester/ vinyl ester automotive	ca. 60 %
4.	GF epoxy balsa/PVC foam wind blade GE	ca. 50 %

  However, it must be assumed that not all the reactor contents could be discharged after each experiment and that some back-mixing occurred. In this respect, some error is to be expected when determining the product quantities.

  The amount of generated gas was much smaller than usual. The gas output was also more inconsistent. In this respect, the quantity determination is not correct. However, since the test was not aimed at measuring the gas volume, the values were not subjected to further testing.
- The analytical results of the gas samples have already been transmitted as requested.
- Despite the selective transport problems with the product fibers forming a felt body, the test operation could be carried out and the required results achieved.

4 Documentation of the test

4.1 Standard operating conditions of the plant

The tests were carried out with the supplied material types. The delivered material was accepted, weighed and prepared for the test.

- The technical equipment had been prepared for testing with some design modifications. The necessity of technical changes and the adjustment of a special technology was derived from earlier tests with material types made of fiber composites. However, the properties of the materials previously used, and the types of materials used in this test differed considerably. It was therefore not possible to transfer the results obtained earlier to the processing of the four types of fibers supplied. However, the effects noted previously could only be recognized when the plant was being operated.
- The process control and measurement technology were adapted to determine and record the effect of the process conditions and new measuring points were added.
- During plant operation, an attempt was made to find and implement suitable solutions for material handling, material conveying and technology for carrying out the processes.

- The fact that the material to be processed did not have transport properties like a (conventional) bulk material, but formed a connected fiber body (e.g. “bird’s nest”) after thermolysis, proved to be the main cause for significantly different requirements on technology and process control.

The system was operated continuously in the standard operating mode and at low temperature settings. The tangled fiber body that built up in the apparatus during the respective test could not be completely moved and discharged. Therefore, after each test, the remaining fiber body had to be removed manually.

The substances and media produced were sampled and the operating conditions documented. During a trial operation, samples were taken and analyzed to determine chlorides, dioxins and furans by absorption from the gas and enrichment in an absorption solution. Samples were also taken to determine the main components of the gas. The samples were analyzed in a certified independent laboratory. The input material was sampled by the customer. Sample quantities of approximately 2 kg of the fiber material produced were made available to the customer for sampling.

4.1.1 Standard operating conditions of the plant Test on 3-9-2018:

Input material: CF epoxy wind blade laminate,
Supplier: GE
Test time: 6:00 AM until 2:30 PM
Sampling: between 12:00 and 2:00 PM
Removal of products and media, determination of quantities for balancing.

System operation on 10.03.2018 is regarded as failure and is not evaluated.
After plant operation, changes were made to the discharge of the screw conveyors.

Plant operation on 20.03.2018:
Application material: GF/CF epoxy hybrid,
Supplier John Deere
Plant operation 7:00 a.m. to 14.30 p.m.
Sampling between 12:00 and 13.30 p.m.
Collection products and media, determination of the quantities for the accounting Plant operation on 23.03.2018:
Application material: GF polyester/ vinyl ester automotive, Plant operation 7:00 a.m.to 14.30 p.m.
Sampling between 11:30 and 13.00 p.m.
Removal of products and media, determination of quantities for balancing.

Plant operation on 28.03.2018:
Application material: GF epoxy balsa/PVC foam wind blade,
Supplier GE
Plant operation 7:00 a.m. to 14.30 p.m.
Sampling between 11:30 and 13.30p.m.
Removal of products and media, determination of quantities for balancing.

4.1.2 Preparation of the plant for the test conditions

Before carrying out the tests on the pilot plant, preliminary tests were carried out with the material "CF epoxy wind blade laminate" in the pilot plant, as a small amount of this was available during the preparation time. The other material types became available immediately before the test date.

The pilot plant was then used to test the test operation at low temperatures and how thermal treatment affects the properties of the fibers. The formation of a fiber body that cannot be removed from the conveying apparatus without mechanical intervention was only determined during the tests on the pilot plant. This effect did not occur in earlier tests with glass fiber composites made of roving mats in combination with epoxy resin.

After the second attempt failed, modified screw discharge devices were manufactured, assembled and tested. Except for the reactor, the modified devices were installed and successfully operated. A conversion of the reactor would have been possible only with a considerably greater effort and loss of time, so it was not considered

Further measures at the pilot plant related to the installation of additional temperature measuring points inside the frame, material feed and the discharge of fibers and coke particles. A new screw conveyor and a new container connection were developed and installed to prevent the escape of fiber particles. Furthermore, the BIO 100 burner system was converted to a lower output to be able to run the system at lower temperatures. The exhaust pipe also had to be modified to reduce the back pressure.

A preliminary test was carried out with the addition of wood particles. However, this measure was not used in the test program.

4.1.3 General conditions of the plant

The plant was operated in this modified configuration, but without any other changes to the main equipment and with settings adapted for this specific test. These settings characterized by the following characteristics:

- System operation with the lower burner with reduced capacity
- Material feeding in short intervals (1 min. each)
- Reactor operation at temperatures from 450°C to 550°C. An adjustment of the temperatures during test operation with the special material over the duration of the test was necessary, the burner power was greatly reduced and partly interrupted due to the reached reactor temperatures (the controllability of the burner is more difficult in the lower control range). The temperatures shown in the diagrams are approximately 50°C higher in the main parts of the apparatus, as a temperature gradient in the reactor still has to be taken into account.
- The temperature was set so low in the tests that on the fourth attempt with PVC the evaporation of the PVC quantity was partially complete.
- Steam generation by means of heat exchangers to supply the reactor with steam at the reactor head was disabled.
- The cracker module for feeding in condensate was not in operation, a small amount of oil was taken from scrubbers 1 and 2.
- Operation of the scrubber circuits in the gas scrubber without recirculation
  - The media levels in scrubbers 1 and 2 were monitored and corrected by refilling or draining,
  - The separators between the scrubbers and the product gas line in the wider area of the plant were checked during operation, ○ The slightly alkaline washing medium was adjusted

by adding NaOH.

4.1.4 Special conditions of the test operation

- The test operation could not be carried out in a standard operating setting due to the nature on the input materials. The operating behavior was observed and measured, and the system settings were adjusted during operation.
- The material was continuously fed in at short intervals. Due to the formation of a felt-like fiber body, a lower throughput was selected and the fill level in the reactor was kept low for better transport. This operating mode had no influence on process control. It only served to support the gasification of the materials. Gas pressure was at a very low level due to the relatively small amount of gas produced. This was expected from the composition of the composites. Quantity measurement with these pressures was not possible with the existing measuring devices. The gas quantity measurement was also not a primary consideration during the tests. This did not have an adverse effect during the test.
- No steam was added to the reactor during the test. No water was added to the reaction mixture and to the post-reactor for balance adjustment and coke degassing during the test.
- The scrubbers ran without changes after the start-up phase when in stationary operation. The differential pressure was at a very low level.
- The oil component was produced in small quantities and was removed from scrubbers 1 and 2 and collected.
- During operation, the levels were kept constant. To prepare a balance sheet, the media were removed from the plant after operation and quantities measured.
- No technical or technological measures beyond those described above were necessary during the trial operation. Except for material-related conveying problems with the fiber body, no failures or malfunctions occurred.

4.1.5 Sampling, analysis, evaluation

The incoming material and the coke were sampled by the client as agreed. The gas samples were captured in gas cylinders and taken to the laboratory (LAG) for standard analysis. There were no particularities regarding sampling and analysis.

The contents of the gas were measured for:

- Chlorine at the fourth experiment by absorption in washing bottles with solvent and analysis at LAG,
- Dioxins and furans in the fourth experiment by absorption in washing bottles with solvent via LAG.

4.1.6 Parameters of the plant operation for this specific test material

The material is fed quasi-continuously via the infeed screws. The material conveyed into the reactor is subjected to evaporation and gasification at the temperature set in the reactor. Because most of the material had glass or carbon fibers that are retained, the intensity of gas formation is low at the set temperature. The fibers form a poorly transportable fiber body over the entire transport section. Therefore, a lower throughput than usual occurred. After entering the reactor, the synthetic resin content did not become plastic but liquid and evaporates at the set temperatures. At the same time, the gasification reaction begins so that a gas flow can be discharged from the reactor.

The product gas is fed from the reactor into the gas scrubber. In gas scrubbing, the condensable components are gradually separated from the generated product gas. It was not intended to completely condense the small quantity of oily components by lowering the temperature in scrubber 1 alone. The desired fractional condensation of light and heavier boiling condensates was achieved in scrubbers 1 and 2. The condensates have a pour point at which the required viscosity is achieved. Deposits were not found in the scrubbers, as was also proven in all previous tests. In scrubber 3, only very small quantities of aqueous condensates formed by the reaction were separated from the gas. No condensate was produced at the sampling points in the following pipe sections. Gas scrubbing technology was not impacted. Thus, the operating behavior was in the normal range.

After gas scrubbing, samples were taken for the analysis of the amounts of chlorine and for the measurement of any dioxins in the gas during the test on 3-28-2018. The settings to determine the operating behavior of the system were:

- the throughput setting via the screw conveyors,
- the reactor temperatures,
- the quantity of the intermittently discharged coke-fiber mixture.

Because of the plant operation, it must be noted that the function of the plant during the processing of the supplied feed material is possible with the restriction, at this time, of a guaranteed uniform discharge of the fibers. Based on the experience gained with this special material during operation, a concept for conveying the fiber body has been derived. Nevertheless, the technology for processing the composites with fibers was demonstrated. The transport problems can be solved with a technical adaptation of the transport system.

The results of the pre-tests and the experience gained from them was essential to adapt the plant. A new procedure based on preliminary tests with the carbon composite material and the need for a modification of the plant prior to the execution of the tests was not possible due to the given time schedule and also due to the other planning.

4.2 Test operation from 3-9-2018 until 3-28-2018

4.2.1 Test description

The material types supplied by the customer were used in the trial operation. The throughput had to be reduced so that the full planned throughput of all the sample materials could not be achieved. Between the tests, phases had to be provided for the partial removal of the fiber body remaining in the systems as noted above.

4.2.1.1 Comments to the test material

The composition of the material from shredded carbon fiber composites and glass fiber composites of different composition was supplied and analyzed by the client. The material batches consisted of heavily shredded material with a proportion of fine material. The composite material was obviously made up of layers of fibers bonded with synthetic resin. A woven rowing structure could not be seen. A proportion of the shredder material had a linear fiber orientation in the composite. The material called "GF epoxy balsa/PVC foam blade" (GE) contained one layer of PVC material.

4.2.1.2 Analysis Input Material

Analysis of the incoming material was taken over by the client and not commissioned from KUG.

4.2.2 Operation of the pilot plant, Measured data

4.2.2.1 Measured values on 09.03.2018

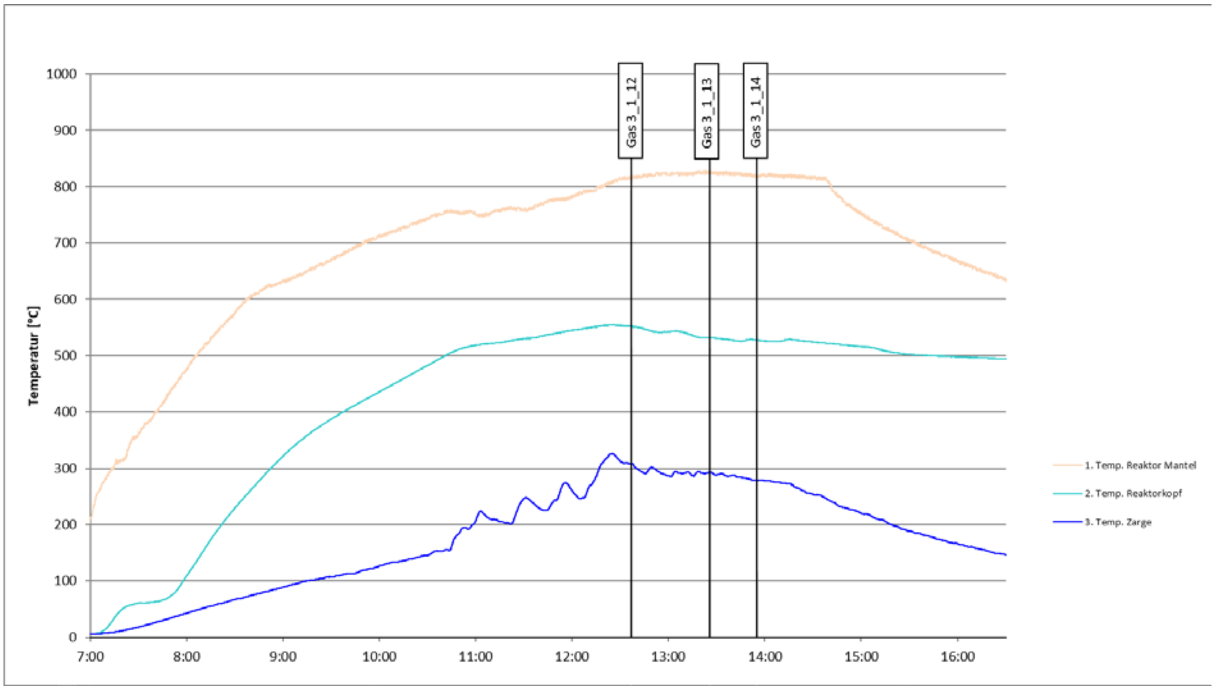

Figure 1: Measured Temperature 09.03.2018

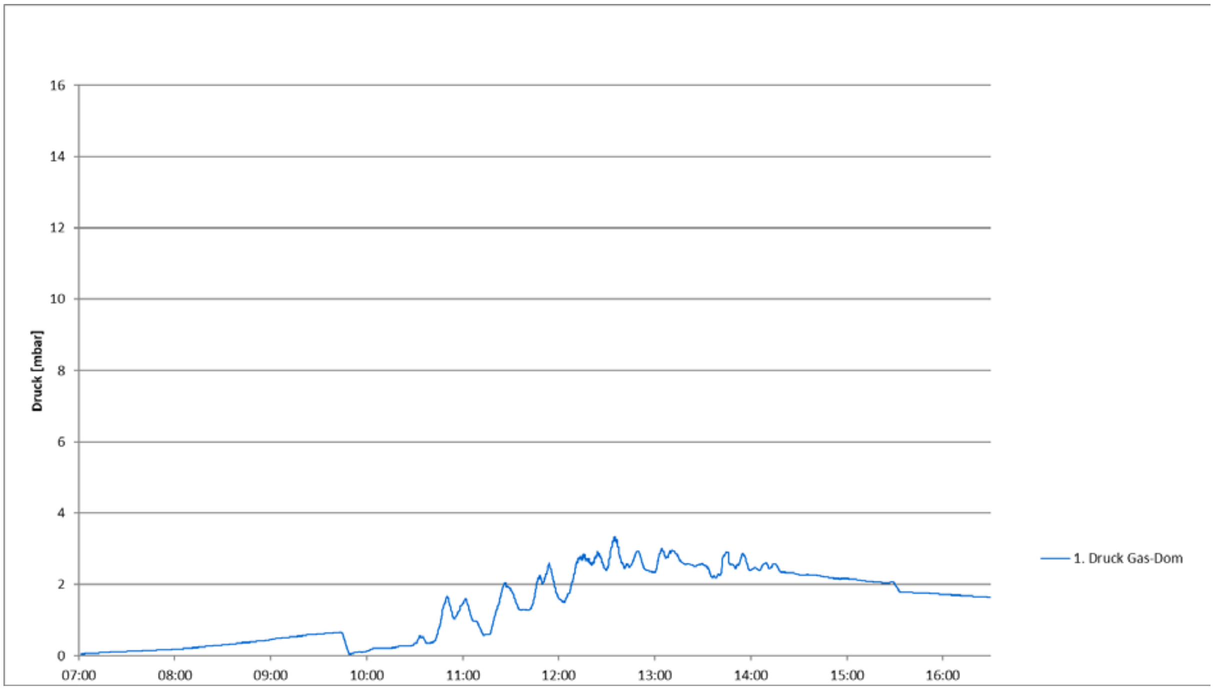

Figure 2: Measured pressure 09.03.2018

4.2.2.2 Measured values on 20.03.2018

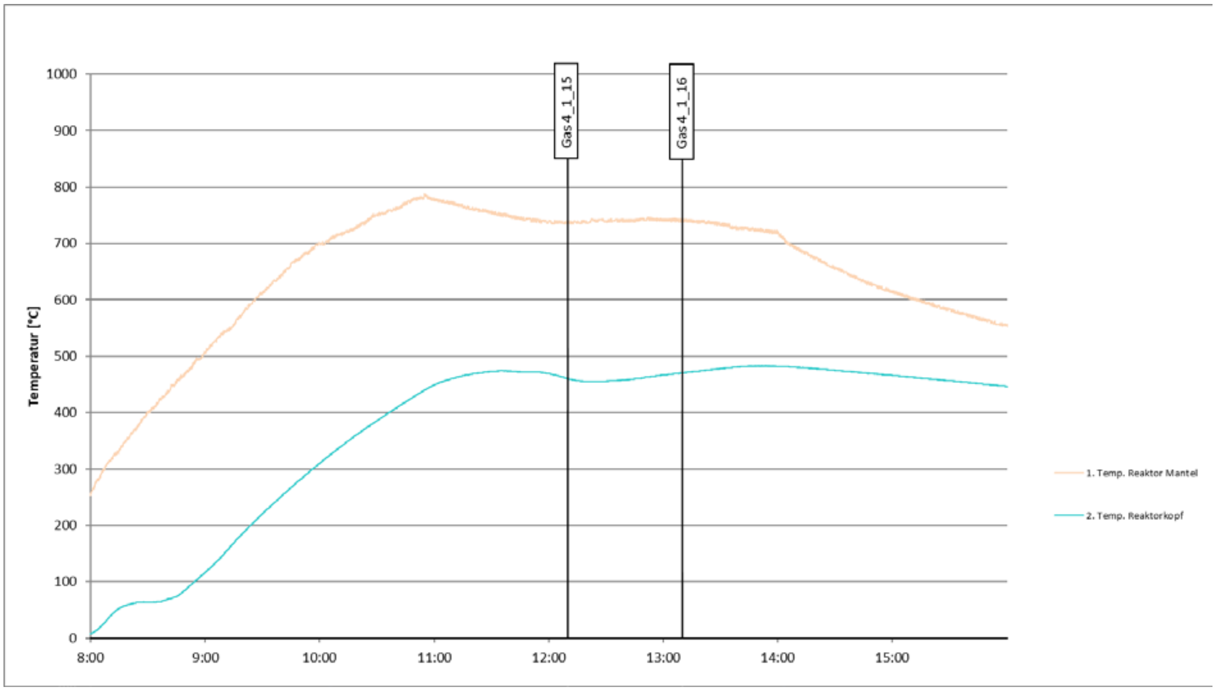

Figure 3: Measured Temperature 20.03.2018

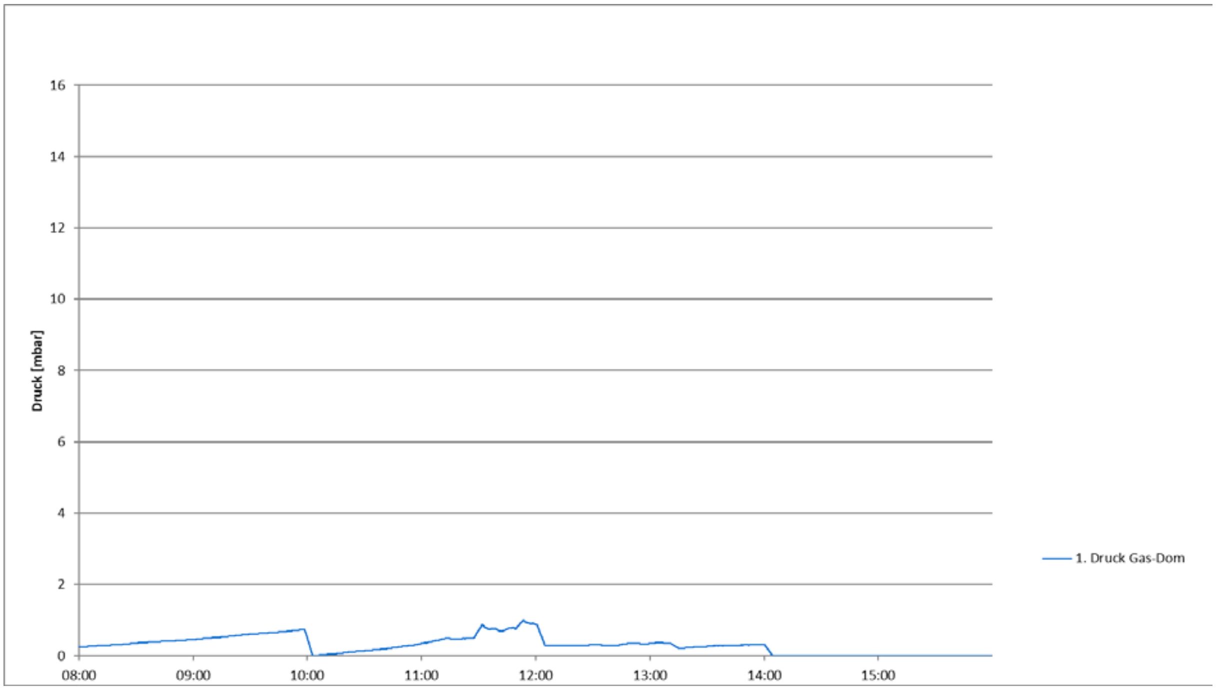

Figure 4: Measured Pressure 20.08.2018

4.2.2.3 Measured values on 23. 03.2018

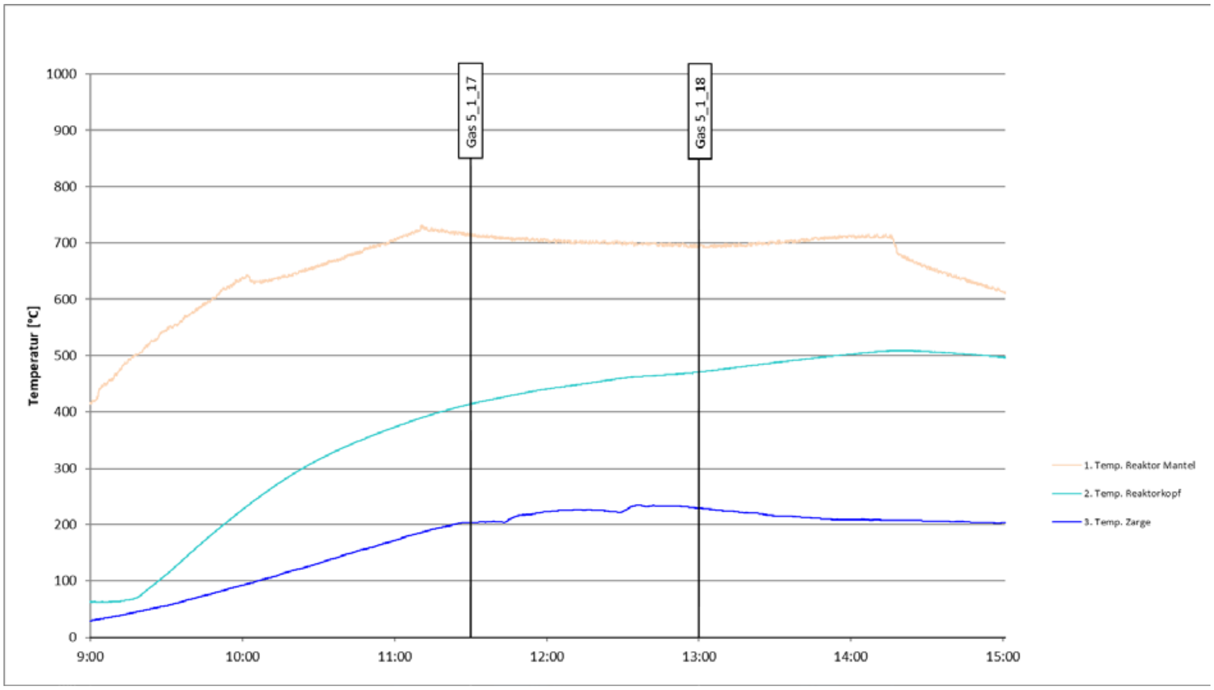

Figure 5: Measured Temperature 23.03.2018

4.2.2.4 Measured values on 28.03.2018

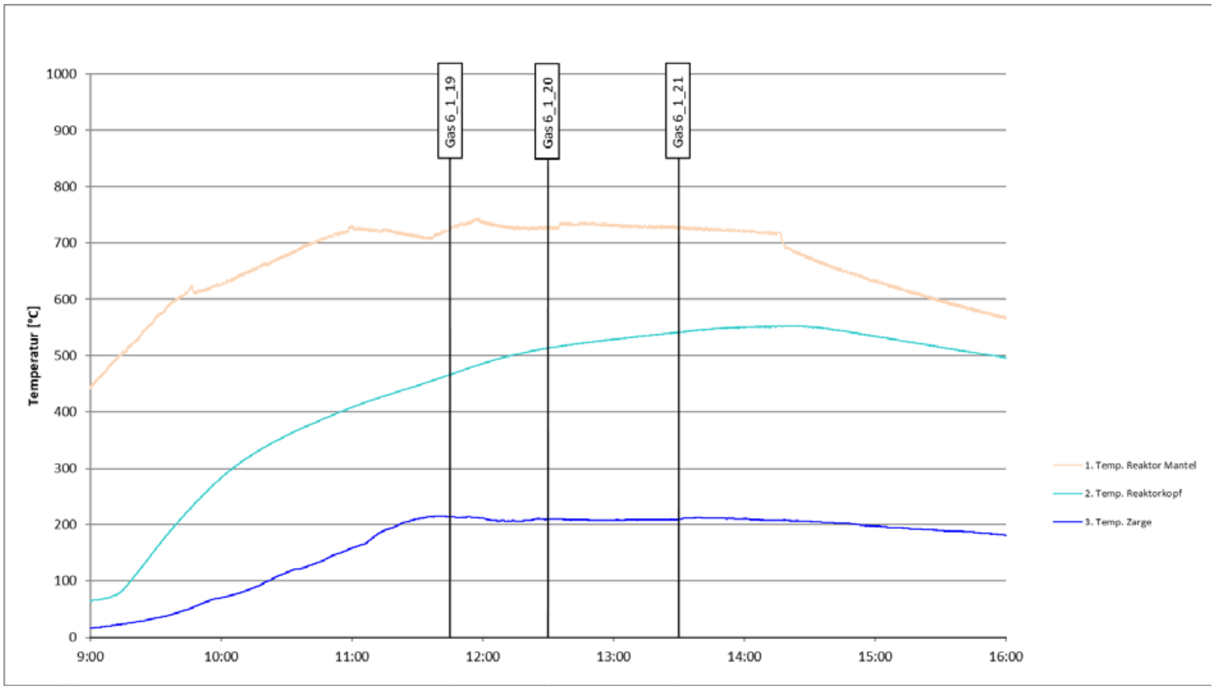

Figure 6: Measured Temperature 28.03.2018

4.2.2.5 Explanation of the measured values and data of the operation on 3-9-2018 Reactor

operation was carried out on 3-9-2018 at temperatures in the reactor chamber of

<600°C. The additional temperature measuring points in the reactor chamber, which are not shown in the diagrams, showed a temperature <550°C. The process was based on these measured values. The measured values recorded and displayed in the diagrams correspond to these additional measured values.

An adjustment of the temperature setting was necessary during the test operation due to the rise in temperatures over the course of the test, the burner output was considerably reduced and partly also interrupted due to the reactor temperatures nevertheless reached. The heat consumption of the processes was considerably lower compared to the usual plant operation and the usually processed material. It is estimated that suppling water in the form of steam at the input would have been advantageous, but this was avoided due to a possible negative effect of the moisture on the fiber properties. The measured temperature values show a good heat transfer in the reactor into the test material despite the tangled fiber body that has formed during the process.

The pressure in the product chamber was very low (below 3 mbar). For collecting the gas samples, the pressure had to be raised in order to be able to fill the gas containers. This can be seen in the pressure diagram from time to time in the slightly higher pressure measured values. A pressure peak at the start of system operation is related to the switching of the sensor, but not to system operation.

The process flow was determined by the reactivity of the material. The material supplied during operation mixed only slightly with the intermediate product (i.e. carbon char) already in the reactor. However, had no significant effects on the test. After all, >70 % of the material supplied consisted of non-reactive fibers which, however, did not form a pile but rather a tangled fiber body during the process. Furthermore, a carbon dust component was formed from the degraded epoxy resin. Heat transfer into the material was good contrary to expectations. The epoxy resin could be liquefied and evaporated sufficiently quickly. The vapor was distributed in the reaction chamber, depolymerized and almost completely chemically converted into gas. In the reactor, the pressure rises irregularly when the material enters the reactor. The pressure increases were sluggish due to the ratio of fiber mass to epoxy resin mass. This effect decreased with the increase in the filling level, as the reaction mass increasingly compensated for the evaporation and conversion of the epoxy resin. The total pressure increases slightly over time due to the increasing mass in the reactor, but the pressure differences become smaller. The smaller pressure changes could be avoided by continuous pumping, which is neither intended nor necessary in the pilot plant.

The reaction speed was normal for the material used, but the amount of gas produced was low due to the material having a low polymer concentration. Quantity measurement was not possible with the existing aperture.

The product gas was fed from the reactor into the gas scrubber. In gas scrubbing, the small quantities of condensable components are separated from the generated product gas. In the present case of operation, only very small amounts of oil-like components were produced, which were condensed and discharged in scrubbers 1 and 2. In scrubber 2, water and the low boiling oily components condense completely due to the set operating mode.

Based on the experience gained in the operation with carbon fiber composites, it can be shown that the thermal and chemical processes can be carried out regularly during processing with this technology. In order to improve the mechanical conveying of the fibers, however, technical adaptations of the conveying equipment, some of which have already been tested, are necessary.

4.2.2.6 Explanation of the measured values and data of the operation on 3-20-2018 Note: should add what material was used.

Reactor operation was carried out at temperatures in the reactor chamber of <500°C on 3-202018 after a change to the screw conveyors and an upstream test. The additional temperature measuring points in the reactor chamber indicated a temperature of <500°C. The measured values recorded and displayed in the diagrams again corresponded well with the additional measured values. A lower temperature could not be set if the epoxy resin was to evaporate completely. From this it can be concluded that the actual temperature reached at the fibers of the fiber body is lower than the displayed temperature.

The pressure in the product chamber was very low - below 1 mbar. Due to the low pressure, sampling had to be carried out elsewhere directly at the post-reactor.

About 70% of the material consisted of non-reactive fibers, which also did not form a pile, but instead became a tangled fiber body during the process. A proportion of carbon dust was also formed. The epoxy resin could be liquefied, decomposed and evaporated. The steam shifted almost completely and was chemically converted into gas. The reaction speed was normal for the material used; the amount of gas produced was low due to the material.

The product gas was fed from the reactor into the gas scrubber. In gas scrubbing, the small quantities of condensable components are separated from the generated product gas. In the present operating case, too, the condensed quantity of oily components that were condensed and discharged in scrubbers 1 and 2 was insignificant.

A comparison of this test operation with results from a previous operation with optic fiber materials revealed significant deviations. This also affected the mechanical conveyance of the fiber body, which showed an even higher crosslinking than in the test with the sample with only carbon fibers. With a discharge device integrated in the meantime as noted above, a solution of the fiber body was achieved - at least to a large extent. However, optimization is still necessary.

The low tendency of the fiber material to maintain a formation with the fibers in strands may be because the glass fiber layers were not inserted into the composite as woven rovings but only as fiber mats.

All other characteristics of the plant operation essentially corresponded to the preceding test.

4.2.2.7 Explanation of the measured values and data of the operation on 3-23-2018

Reactor operation was carried out on 3-23-2018 at temperatures in the reactor chamber of approximately 500°C. The additional temperature measuring points in the reactor chamber showed a slightly higher temperature of <550°C. The gas development at these temperatures was roughly comparable to that of the preliminary test.

The pressure in the product chamber was very low and obviously not representative. The measurement was not evaluated. Sampling had to be carried out elsewhere directly at the post-reactor as noted previously.

Approximately 60% of the material also consisted of non-reactive fibers, which also did not form a pile but instead formed a tangled fiber body during the process. The epoxy resin was gasified. The amount of gas produced was low due to the small amount of polymeric material present.

As in the preliminary test, the integrated discharge device led to a solution of the tangled fiber body. However, optimization is still necessary.

All other characteristics of the plant operation essentially corresponded to the preceding test.

4.2.2.8 Explanation of the measured values and data of the operation on 3-28-2018

Reactor operation was carried out on 3-28-2018 at temperatures in the reactor chamber of approximately 550°C. The additional temperature measuring points in the reactor chamber showed a slightly higher temperature of 550°C to 580°C. The gas production was visibly greater than in the previous test due to the PVC content.

Once again, the pressure in the product chamber could not be measured. Obviously, the set temperature in the area of the pressure measuring point was too low to prevent condensation of the plasticizer component of the PVC. Water vapor is fed into the reactor head and the post-reactor for flushing. This feeding can be carried out for tests with glass fibers. However, due to the low operating temperature, the amount injected was small and was obviously not sufficient to displace the steam produced from the epoxy resin. This then condenses at the somewhat cooler points of the reactor, since the evaporation temperature of the epoxy resin and the reactor temperature must not differ very much to avoid thermal stress on the glass fibers. No appropriate changes could be made during operation. Since the pressure is not a relevant process variable in this case, the pressure is not evaluated. The gas was again sampled directly at the post-reactor.
In this experiment, absorption samples for the determination of chlorine and dioxins/furans were also taken. The evaluation of these samples is presented in the section Evaluation of Analyses.

The material consisted of <50% non-reactive fibers, which also did not form a pile but formed a tangled fiber body during the process. The epoxy resin and the PVC contained in the composite were gasified. The gasification of the PVC component increased the volume of gas generation. However, under the operating conditions and the residence time, the plasticizer components could not be gasified below approximately 550°C. Further identification of the evaporation and gasification conditions can be achieved by further tests. However, it must be determined whether such tests and the measures associated with them are necessary.
All other characteristics of the plant operation essentially corresponded to the preceding tests.

4.2.3 Additional information to the plant parameters

- Gas cleaning: Scrubber 1: 50 °C, Scrubber 2: 25 °C, Scrubber 3: 20°C
- All sampling according to schedule.

4.2.4 Mass balance and analysis results

4.2.4.1 Test on 09.03.2018

From the input quantity supplied (preliminary test: 40 kg, main test on 09.03.3018: 100 kg) remain:

- 69 % fibers and coke plus possibly approximately 5 %, which could not be discharged,
- approximately 20 % gas with a humidity of approximately 1 % water,
- approximately 2 % water.

It was not possible to draw up an exact balance sheet, but the data are reliable and can be reproduced with a high degree of probability.

Despite mechanical cleaning of the apparatus after the test, zones remain which cannot be reached. The residual quantities remaining therein, which became mixed with the material of the subsequent tests or remained longer in the reactor, are estimated at 5 %. The effect of back-mixing can be seen in the products of the follow-up tests.
The gas humidity was derived from the difference of the standard analysis to 100 %, which is approximately 1 %. This test confirms an earlier statement that most of the components not covered by the standard analysis consist of water.

4.2.4.2 Produced Gas Analysis

	09.03.2018		
Major Components [Vol-%]	**Gas 3_1_12**	**Gas 3_1_13**	**Gas 3_1_14**
H_2	29,1	38,6	32,1
O_2	0,66	1,1	1,4
N_2	2,2	3,5	6,4
CH_4	28,1	23,4	24,3
CO	26,0	23,2	25,0
CO_2	9,6	7,9	7,8
Ethane	0,84	0,36	0,36
Ethene	2,7	1,6	1,6
Propane	<0,01	<0,01	<0,01
Propene	0,8	0,33	<0,92
i-Butane	<0,01	<0,01	<0,01
n-Butane	<0,01	<0,01	<0,01
Molecular weight	18,8	16,5	18,2
Density kg/m^3	0,8	0,7	0,8
Heating value	5,6	4,7	4,8
Wobbe index kWh/m^3	6,7	6,2	6,1

Table 1: Gas compositions 09.03.2017 (Measured in Volume Percent)

Due to the high hydrogen content, the density and the volume-related calorific value are low. The volume of gas produced is increasing in the opposite direction. The nitrogen and oxygen contents shown in the gas analysis have permeated into the sample vessel through sampling / transport. They are therefore not a produced gas component and must be deducted.

The balance sheet shows the gas mass and not the gas volume. The calorific values related to the mass are correspondingly higher for the table data.

4.2.4.3 Notes on the gas analysis results

In the test on 09.03.2018 a gas composition with an average calorific value was produced, although the hydrogen content (based on volume %) is also high and the gas therefore has a lower density. However, this is also offset by a comparatively high carbon monoxide content. The carbon dioxide content and the components with 2-4 carbon atoms are in comparatively low concentrations. The low carbon dioxide content is not typical for the usual operating settings and the equilibrium reaction, since the test was run at a low temperature setting.

A main reason for the gas composition, however, is also due to the gasification of the epoxy material. The gas equilibrium reaction could be influenced by the addition of water vapor. This would lead to an increase in the amount of gas, a further increase in the hydrogen content and carbon monoxide.

4.2.4.4 Trial on 20.03.2018

The glass fiber composite material yielded
70 % fiber and coke plus possibly approximately 3 %, which could not be discharged and approximately

25 % gas with a humidity of approximately 1 % water produced.

It was not possible to draw up an exact balance sheet, but the data are reliable and could be reproduced with a high probability.
Despite mechanical cleaning of the apparatus after the test, zones remain which cannot be reached. The residual quantities remaining therein, which mixed with the material of the subsequent tests or remain longer in the reactor, are estimated to be <5 %. The gas humidity was also derived from the difference of the standard analysis to 100 %, which is approximately 1 %.

4.2.4.4 Produced Gas Analysis

	20.03.2018		
Main Components [Vol-%]	**Gas 4_1_15**	**Gas 4_1_16**	
H_2	26,4	Air	
O_2	3,0	in the Probe	
N_2	15,3		
CH_4	29,9		
CO	14,3		
CO_2	7,9		
Ethane	1,3		
Ethene	0,82		
Propane	0,09		
Propene	0,05		
i-Butane	<0,01		
n-Butane	<0,01		
Molecular weight	18,9		
Density kg/m^3	0,8		
Heating value	4,7		
Wobbe index kWh/m^3	5,8		

Table 2: Gas Compositions 20.03.2017 (Measured in Volume percent)

Due to the hydrogen content, the density and the volume-related calorific value are low. The volume of gas produced is increasing in the opposite direction. The nitrogen and oxygen contents shown in the gas analysis have leaked into the sample vessel during sampling / transport. They are therefore not a gas component of the reaction and must be deducted.

The balance sheet shows the gas mass and not the gas volume. The calorific values related to the mass are correspondingly higher for the table data.

4.2.4.5 Notes on the gas analysis results

In the test on 20.03.2018, a gas composition with a high calorific value was produced, although the hydrogen content (based on volume %) was also high and the gas therefore has a lower density. However, this is also offset by a comparatively high carbon monoxide content. The carbon dioxide content and the components with 2-4 carbon atoms are comparatively low in concentration. The low carbon dioxide content is not typical, because the test was run at a low temperature setting for the equilibrium reaction.

A main reason for the gas composition is also the gasification of the epoxy material. The gas equilibrium reaction could be influenced by the addition of water vapor. This would lead to an increase in the amount of gas, a further increase in the hydrogen content and carbon monoxide.

4.2.4.5 Attempt on 23.03.2018 from the

fiberglass composite material were

- • 60% fibers and Coke plus possibly about 3%, which could not be removed and
- Approximately 30% gas with a humidity of approximately 4% water produced. It was not possible to draw up an exact balance sheet. This is shown in the figures. However, the data can be loaded, reproducibility is to be expected.

Despite mechanical cleaning of the apparatus after the test, zones remain which cannot be reached. The residual quantities remaining therein, which mixed with the material of the subsequent tests or remain longer in the reactor, are estimated to be <4 %. The gas humidity was also derived from the difference of the standard analysis to 100 %, which is approximately 2 %.

4.2.4.6 Produced Gas Analysis

	23.03.2018		
Main Components [Vol-%]	**Gas 5_1_17**	**Gas 5_1_18**	
H_2	18,9	20,5	
O_2	0,86	0,59	
N_2	3,3	2,1	
CH_4	24,2	26,1	
CO	13,5	13,0	
CO_2	22,2	21,9	
Ethane	4,2	4,5	
Ethene	4,7	4,2	
Propane	0,91	0,98	
Propene	2,1	2,1	
i-Butane	0,04	0,05	
n-Butane	0,13	0,1	
Molecular weight	24,2	23,5	

Density kg/m^3	1,1	1,0	
Heating value kWh/m^3	6,1	6,2	
Wobbe index kWh/m^3	6,7	6,9	

Table 3: Gas compositions 23.03.2017 (Measured in Volume percent)

The gas composition of this test differs from the previous ones by the type of synthetic resin used in this material composite. The material contains polyester/vinyl esters, resulting in a different composition of the reaction products. The hydrogen content is lower, the carbon oxides and the hydrocarbons have higher proportions. This leads to an increase in density and volume-related calorific values. The volume of gas produced is decreasing in opposite directions.

4.2.4.7 Notes on the gas analysis results

The test on 23.03.2018 produced a gas composition with a calorific value determined by the methane content and the carbon oxides. The higher carbon dioxide content is typical of a low temperature driving style and the associated equilibrium reaction.

A main reason for the gas composition in this test is the gasification of the plastic material polyester/vinyl ester. The gas equilibrium reaction could be influenced by the addition of water vapor. This would lead to an increase in the amount of gas, hydrogen and carbon monoxide.

4.2.4.8 Attempt on 28.03.2018

- The glass fiber composite material has been ca. 50 % Fibers and coke plus possibly about 5% which could not be removed and ca. 35 % Gas with a humidity of about 1% water produced.

It was not possible to draw up an exact balance sheet. This can be seen from the numerical values. However, the information is reliable and could be reproduced with high probability.

Despite mechanical cleaning of the apparatus after the test, zones remain which cannot be reached. The residual quantities remaining therein, which mix backwards, are estimated to be <5 %. The gas humidity was also derived from the difference of the standard analysis to 100 %, which is approximately 1 %.

4.2.4.9 Produced Gas Analysis

	28.03.2018		
Main Components [Vol-%]	**Gas 6_1_19**	**Gas 6_1_20**	**Gas 6_1_21**
H_2	20,0	Air	Air
O_2	0,73		
N_2	3,9		
CH_4	37,2		
CO	18,9		
CO_2	6,5		
Ethane	3,9		
Ethene	5,7		
Propane	0,45		
Propene	1,3		
i-Butane	0,01		
n-Butane	0,06		
Molecular weight	19,7		
Density kg/m³	0,9		
Heating value	7,2		
Wobbe index kWh/m³	8,7		

Table 4: Gas Compositions 28.03.2017 (Measured in Volume percent)

In this test, the sampling of two samples failed. The samples contained 50 % and 55 % air and are therefore not representative and are not presented. Therefore, only one analysis of the experiment is available. The nitrogen and oxygen content also shown in this gas analysis have leaked into the sample vessel through sampling / transport. They are therefore not a gas component of the reaction and must be deducted.

Notes to the gas analysis results

In the test on 28.03.2018, a gas composition with a comparatively high calorific value was produced, which is determined by the methane content and the carbon oxides. The hydrocarbon content also contributes to increasing the calorific value.

The material contained PVC, which influences the gas equilibrium reaction. The gas formation is thus based on the depolymerization of the epoxy resin, which differs from the preceding material types, on the plastic content of the PVC and the gasified plasticizer. For the decomposition of the plasticizers, the temperatures set for the test are already borderline. Higher temperatures are required for complete decomposition. Components that are not degraded to gas therefore condense at cooler points in the reactor. These must be rinsed increasingly with steam or a higher temperature must be set in order to degrade the components.

Since the thermolysis of this experiment resulted in a higher chloride content due to PVC, the gas scrubber was operated with slightly basic circulation media and the gas was thus purified. In addition, absorption samples were enriched for dioxin measurement over a period of two hours. The concentrations of chlorine and dioxin related to the gas quantity are calculated.

4.2.4.10 Chlorine-Analyseis, Samples 6_1_23/1 and 6_1_23/2

Investigated parameter	Analysis Value	Dimension
Chlorides	1,3	mg/l
Chlorides	1,2	mg/l

Table 5: Analysis for Gas using Absorption - 28.03.2018

The gas was cleaned in the gas scrubber cascade with three scrubbers. During the test on 28.03.2018 with PVC-containing material, samples were taken from the gas stream via washing bottles for the determination of chlorides and dioxin/furans and analyzed in the laboratory. The analyses of the chloride and dioxin/furan concentrations absorbed in the scrubbing liquid were converted to the quantity of gas used.

The chloride residues in the purified product gas were determined with 10 mg/m3 gas. This means that the concentration is below the limit value. The efficiency of the gas scrubbing is thus verifiable.

When using the specified material, the neutralization with NaOH and $Ca(OH)_2$ should be intensified by a higher concentration of the neutralizing agent if necessary to further reduce the chloride in the product gas, as this appears to be appropriate for the amount of chloride present in the input. A fourth scrubber can also be integrated into the gas scrubber. In previous experiments, a higher concentration of the neutralizing agent caused the desired separation effect of chlorine.

It is noted that given the configuration of the pilot plant and the described technology, when using the produced product gas as heating gas, the chlorine content drops to approximately 3 mg/m^3 as a result of combustion; and is thus far below an environmentally relevant limit value. This value can be further reduced by installing a 4th scrubber.

4.2.4.11 Dioxin/Furan analysis, Sample No. 6_1_22

Investigated parameter	Dimension	28.03.2018 6_1_22	Procedure
2,3,7,8-Tetrachlordibenzodioxin	pg/l	<1,3	Vorschlag DEV, Kapitel F33
1,2,3,7,8-Pentachlordibenzodioxin	pg/l	<1,2	Vorschlag DEV, Kapitel F33
1,2,3,4,7,8-Hexachlordibenzodioxin	pg/l	<1,5	Vorschlag DEV, Kapitel F33
1,2,3,6,7,8-Hexachlordibenzodioxin	pg/l	<1,4	Vorschlag DEV, Kapitel F33
1,2,3,7,8,9-Hexachlordibenzodioxin	pg/l	<1,5	Vorschlag DEV, Kapitel F33
1,2,3,4,6,7,8-Heptachlordibenzodioxin	pg/l	<0,9	Vorschlag DEV, Kapitel F33
Octachlordibenzodioxin	pg/l	<1,1	Vorschlag DEV, Kapitel F33
2,3,7,8-Tetrachlordibenzofuran	pg/l	<1,3	Vorschlag DEV, Kapitel F33
1,2,3,7,8-Pentachlordibenzofuran	pg/l	<1,0	Vorschlag DEV, Kapitel F33

2,3,4,7,8-Pentachlordibenzofuran	pg/l	<1,0	Vorschlag DEV, Kapitel F33
1,2,3,4,7,8-Hexachlordibenzofuran	pg/l	<1,1	Vorschlag DEV, Kapitel F33
1,2,3,6,7,8-Hexachlordibenzofuran	pg/l	<1,0	Vorschlag DEV, Kapitel F33
2,3,4,6,7,8-Hexachlordibenzofuran	pg/l	<1,0	Vorschlag DEV, Kapitel F33
1,2,3,7,8,9-Hexachlordibenzofuran	pg/l	<1,3	Vorschlag DEV, Kapitel F33
1,2,3,4,6,7,8-Heptachlordibenzofuran	pg/l	<1,1	Vorschlag DEV, Kapitel F33
1,2,3,4,7,8,9-Heptachlordibenzofuran	pg/l	<1,4	Vorschlag DEV, Kapitel F33
Octachlordibenzofuran	pg/l	<1,2	Vorschlag DEV, Kapitel F33
Sum PCDD (Tera-Octa)	pg/l	<0,9	Vorschlag DEV, Kapitel F33
Sum PCDD (Tera-Octa)	pg/l	<11	Vorschlag DEV, Kapitel F33
Sum PCDD + PCDF (Tera-Octa)	pg/l	<20	Vorschlag DEV, Kapitel F33
Sum PCDD + PCDF (I-TE/NATO CCMS) excl. BG	pg TEQ/L	0	Vorschlag DEV, Kapitel F33
Sum PCDD + PCDF (I-TE/NATO CCMS) incl. BG	pg TEQ/L	3,44	Vorschlag DEV, Kapitel F33
Sum PCDD + PCDF (TEQ/WHO 1997) excl. BG	pg TEQ/L	0	Vorschlag DEV, Kapitel F33
Sum PCDD + PCDF (TEQ/WHO 1997) incl. BG	pg TEQ/L	4,04	Vorschlag DEV, Kapitel F33

Table 6: Analysis for Dioxin and Furan in Gas by Absorption - 28.03.2018

The dioxin determination proved that all dioxin/furan concentrations are below detectable limits. The numerical values are not the measured values, but the lower limit values for the measurement procedure, i.e. the values are smaller than the lower limit values. It was expected that no dioxin formation would occur when the thermolysis process was used, as the intermediate product in the reactor has a reducing effect hence preventing formation of dioxins.

5 *Evaluation of the results*

The main results from plant operation with the composite material types are summarized as follows:

- The plant operation with the type of material used was successfully carried out. The technology for thermal and chemical conversion of the matrix, as carried out in the pilot plant, is suitable for processing the type of material with the restriction of the mechanical conveyance of the fiber body, which is formed by the disintegration of the composites. The conveying of the tangled fiber body requires technical measures on the conveying equipment, some of which have now been implemented and successfully tested.
- A fiber body containing carbon dust is produced, which can be further mechanically processed to obtain aligned fibers and separate the carbon dust. Except for the type of material, which contained a PVC content, the glass fiber/carbon content produced was 60 to 70% of the input quantity.
- Furthermore, a product gas is produced that can be used to generate the required energy.

- Among other things, samples were taken for the detection and the analysis proved that no dioxin is produced or that any dioxin present is decomposed.
- The effects of the technology on the processes in the reactor and in gas scrubbing are explained in the report.
- Four material types were processed in succession. During the transition from one type of material to the other, a back-mixing of the fiber components occurs in the transition phase despite mechanical cleaning of the apparatus, since the fiber body cannot be completely discharged.
- The operating behavior of the system has been demonstrated.
- The chemical and thermal processes examined are suitable for the objectives of material processing. Technical adaptation measures to the equipment are required for the conveying processes.
- The analysis was prepared in accordance with the agreement. Except for gas samples, supplementary analyses may be performed from retained samples. The report evaluates the test results and the analysis results.

Appendix B:
TEA Assumptions

- **Cost and Capital Investment (CAPEX) -** Estimates provided by CHZ Technologies for the Thermolyzer™ Technology. The cost/CAPEX portion of the model used the mass and energy balance (summarized in Table 11) and projected scale-up from pilot scale operation using the four representative (wind and automotive) composites scrap and EOL materials depicted in Figure 3. Specifically, the TEA model used the following inputs (see Table Below)
    - Yields (product and waste) – Mass balance
    - Variable Cost (energy to operate and excess energy) – Energy balance
    - Other Variable Cost (waste treatment, utilities, etc.) – Based on CHZ scale-up
    - Fixed Cost (annual fixed operator/maintenance costs) – Based on CHZ scale-up
    - Capital Investment (Greenfield - standalone plant and Brownfield – process to existing plant) – Based on CHZ scale-up

Capacities		CAPEX	Other VC	Fixed Cost
kta RM	kta FP	$mm	$/kg FP	$mm
3.0	1.7	11.2	0.02	2.4
30.0	16.8	18.2	0.02	2.4
60.0	33.5	31.9	0.02	2.4
120.0	67.0	56.9	0.02	2.4

Mass Balance		
FP Yield	0.56	kg FP/kg RM
Waste Yield	0.01	kg Waste/kg RM

Energy Balance		
Total Energy (TE)	9,525	BTU (NG Eq)/kg FP
	TE to run Thermolyzer™ process	
Recovered Energy (RE)	15,525	BTU (NG Eq)/kg FP
	RE from organic/resin content	
Net Energy (NE)	(6,000)	BTU (NG Eq)/kg FP
	NE - Excess energy produced = TE - RE	
NG Price (2018/19)	*2.95*	$/MMBTU

FP - Finished Product (Recovered Sellable Fiber)
RM - Raw Material (Composite Scrap/EOL Feeds Thermolyzer™
NG - Natural Gas

- **Demand/Fiber Value (Volume/Cost to Value in the P&L Tables 14-17) projections for recovered GF, CF and GF/CF Hybrid fibers from Thermolyzer™ were estimated with guidance from the IAMCI team/partners (ACMA, CSP, etc.)**
    - Demand – Since the TEA was completed for a single Thermolyzer™ with a recovered product capacity of 17 kton/yr (CF and high CF/GF Fiber) to 67 kton/yr (GF and low CF/GF fiber), which are significantly lower that the total NA srap/EOL composites produced, the ramp

        rate assumed end use markets can be developed to create demand pull-though to fill a single Thermolyzer facility.
    - Recovered Fiber Value
        - Recovered GF Value of $0.6/kg assumed 30-50% discount versus the "on-purpose" GF due to inferior performance associated with recovered products (e.g., degradation of sizing, higher variability in fiber length, reduced fiber length, etc.)
        - Recovered CF values were similarly discounted versus the "on-purpose" CF based on the following recovered fiber lengths
            - Long carbon fiber (LCF, 1 inch fiber length) market value of $16/kg
            - Milled carbon fiber (MCF, 1/16 inch fiber length) market value of $8.0/kg
    - A critical next phase for ACMA/IACMI to do: define and develop applications (i.e., BMC, SMC, Extrusion/Injection Molding, etc.) for recovered fibers that both sustainable with potential growth. Once these markets/applications are defined, the TEA needs to be update to reflect "cost to value" for that specific segment
- **Financial Valuation assumptions,**
    - 5 YR P&L - Projected (estimated) time to reach market maturity
    - Other key assumption: Discount Rate = 6%, SG&A = 5% and Terminal Value = 5X EBIDTA
    - Other assumptions: Tax Rate = 28%, Days Inventory, A/P and A/R = 45 days/ea
    - Key Changes in TEA Model - Cost to Value (CF and GF/CF Hybrids) & CAPEX Subsidy (0%, 25%, 50% and 75%)
- **Key Financial Metrics:** NPV6, IRR, ROCC, Payback and Cash Flow (5YRS)