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Study of Carbon Fiber Reinforced Polymers technology and market.

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Abstract

The growing knowledge and awareness of the environmental condition have driven to governments to implement restrictions on energy use, levels of efficiency and resources use, aiming for higher sustainability targets.

Transportation an energy sectors have found on CFRP (Carbon Fiber Reinforced Polymers) technology a solution to achieve the highest levels of mechanical performance under low weights and is therefore a key enabling technology that makes possible the electric and hydrogen vehicles, the wind energy production and reduced levels of air transport emissions among others.

This Master Thesis comprehends the study of the CFRP technological from a technical and market perspective pursuing the holistic comprehension of the system. This analysis will employ bibliographic references, quantitative and qualitative analysis and graphical visualizations to decompose complexity and to compile key data for the reader. For market forecasting time series forecasting techniques will be employed.

At technical level the study covers the definition of the CFRP systems and subsystems/components, their characterization, production, manufacturing, the state of the art on the design methodology, recyclability and life-cycle assessment. This study will also detail current applications of the CFRP technology on multiple products.

The market study involves the analysis of the European political context and regulations affecting CFRP adoption, the stakeholders of the system, the cost analysis of the CFRP, market quantification and the future market forecasting.

The study produced has compiled relevant information from multiple sources in a summarized, relational and organized way, it has also produced useful datasets of CFRP technology and market; qualitative and quantitative analysis together with data visualization techniques have revealed multiple insights. The life-cycle assessment has quantified the environmental effects of CFRP production. A forecast of CFRP sells, prices and market value has been produced.

Studies performed have revealed CFRP as an outstanding technical material at an advanced level of Technological Readiness; with well stablished manufacturing methods, characterization, mechanical modelization, failure modes understanding, and with available commercial software supporting design workflows and simulation.
Technological developments and downwards prices allow for companies to change classical materials such as steel with CFRP, not only as a way to achieve higher levels of performance but also as a way to produce products with less parts in a lean and flexible way, it entails, therefore a paradigm shift; CFRP environmental impact is conditioned by high levels of energy needed to produce fibers and difficulties to recover fibers from thermoset matrices, to achieve environmental improvements versus other engineering materials more than one life cycle is needed, to achieve that, new methods and approaches are in development such as Supercritical Water or design for End Of Life strategies.

CFRP and Carbon Fiber markets are supported as a key enabling technology to achieve the efficiency and clean energy targets imposed by Europe being key market drivers on automotive, aerospace and energetic markets; CFRP cost structure find it highest contributions on the energy and labor needed to carbon PAN (Polyacrylonitrile) based fibers, the latter costs are driven by petroleum feedstock prices; time series forecasting reveals CF sells to double in the 2022-2027 period.

Resumen

El creciente conocimiento y preocupación por las condiciones medioambientales han llevado a los gobiernos a implementar restricciones en el uso de la energía, en los niveles de eficiencia y en el empleo de recursos con el objetivo de alcanzar mayores tasas de sostenibilidad.

Sectores como el del transporte o el energético han encontrado en la tecnología CFRP (Polímeros Reforzados con Fibra de Carbono) la solución para alcanzar los objetivos gubernamentales. Esta tecnología permite alcanzar los mayores niveles de desempeño mecánico en estructuras excepcionalmente ligeras, y supone, por lo tanto una "Key Enabling Technology" que hace posible soluciones como los vehículos eléctricos y de hidrogeno, la producción de energía eólica o grandes de reducciones de consumo de combustible en el transporte de pasajeros.

Esta Tésis de Máster comprende el estudio de la tecnología y del mercado de los CFRP persiguiendo una comprensión conjunta del sistema. Este estudio se basará en la recopilación, filtrado y síntesis de referencias bibliográficas, en el análisis cualitativo y cuantitativo y el apoyo de los mismos mediante técnicas de visualización de datos para describir la complejidad recogiendo datos relevantes.

A nivel técnico el estudio cubre la definición de los sistemas CFRP y los distintos subsistemas/componentes, su caracterización, producción, manufactura, el estado del arte en las metodología de diseño, la reciclabilidad y el análisis del ciclo de vida. Este estudio técnico también mostrará aplicaciones actuales de la tecnología CFRP en múltiples productos.

El estudio de mercado involucra el análisis del contexto político europeo y las regulaciones afectando la adopción de tecnología CFRP, los distintos actores en el mercado, el análisis de costes del CFRP, la cuantificación de los mercados y la previsión de mercados futuros.

El estudio llevado a cabo ha recogido información relevante de múltiples fuentes de manera sintética, relacional y organizada, también ha producido datasets útiles sobre el mercado y tecnología CFRP; las técnicas de análisis cualitativo, cuantitativo y las técnicas de visualización de datos han relevado múltiples conclusiones extraídas de la información recogida. El análisis del cicló de vida ha cuantificado los efectos medioambientales del empleo de los CFRP. Se han generado predicciones de precios, ventas y mercado de los CFRP.

Los estudios realizados han relevado que el CFRP como un material con características técnicas excepcionales en un nivel avanzado de madurez tecnológica; con una caracterización bien establecida a nivel químico, físico y mecánico, sistemas de manufactura robustos, con modelos matemáticos capaces de representar el comportamiento mecánico, con la identificación de múltiples modos de fallo de los compuestos y con metodologías de diseño de sistemas soportadas por software que permite el correcto flujo de trabajo para el diseño, optimización y simulación de productos de CFRP.
Los avances tecnológicos y la reducción de los costes de estos sistemas permiten a la compañías substituir materiales tradicionales como el acero por CFRP, no solo como una forma de alcanzar mayores niveles de desempeño mecánico sino como una forma de producir productos con menor número de partes y con menos medios de producción de una manera flexible y supone por lo tanto un cambio de paradigma en la producción y diseño de bienes; el impacto medioambiental del uso de los CFRP está condicionado por los altos niveles de energía necesarios para producir las fibras y las dificultades para recuperar estas de matrices de polímeros termoestables, para alcanzar mejoras medioambientales frente a otros materiales como el acero, es necesario más de un ciclo de vida, para alcanzarlo, nuevos métodos y enfoques de diseño están en desarrollo como la recuperación de fibras de carbono con SuperCryticalWater o el diseño para el final de vida.

Los mercados del CFRP y de la fibra de carbono están soportados en la medida en que se tratan de una Key Enabler Technology para alcanzar los niveles de eficiencia y energía limpia impuestos por las autoridades europeas provocando una tendencia positiva en los mercados de la automoción, aeronáutico y energético; la estructura de costes de CFRP encuentra sus mayores contribuciones en la energía y trabajo necesarios para el carbonizado de las fibras de PAN (Poliacrilonitrilo); los costes de producción de las últimes están en gran medida sujetos al el precio del petróleo; las predicciones de series temporales revela que las ventas de fibra de carbono se doblarán en el periodo 2022-2027.

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List of abbreviations / Glossary

CFRP: Carbon Fiber Reinforced Polymers
CF: Carbon Fiber
LCA: Life Cycle Assessment
CLT : Classical Laminate Theory
CAD: Computer Aided Design
CAM: Computer Aided
CAE: Computer Aided Engineering
WP: Work Package
PAN: Polyacrylonitrile
EV: Electric Vehicle
DMSO: Dimethyl Sulfoxide
PEEK: Polyetheretherketone
PEI: Polyetherimide
PP: Polypropylene
PE: Polyethilene
PC: Polycarbonate
PA6: Poliamide, Nylon
PET: polyethylene terephthalate
ABS: Acrylonitrile Butadiene Styrene
GFRP: Glass Fiber Reinforced Plastic
AFRP: Aramid Fiber Reinforced Plastic
BFRP: Basalt Fiber Reinforced Plastic
RTM: Resin Transfer Molding
AFP : Automated Fiber Placement
GHG: Global Greenhouse Gas
LCI: Life Cycle Inventory
EOL: End Of Life
SCW: Super Critical Water
UCW: Unitary Cost Carbon Waste
UCF: Unitary Cost Recovered Fiber
GWP: Global Warming Potential
PESTLE: Political Economic Sociological Technological Legal Environmental
EU: European Union
ETS: European Trading System
LULUF: Land Use and Forestry Regulations
ICE: Internal Combustion Engine
NGL: Natural Gas Liquids
FCEV: Fuel Cell Electric Vehicle
EV: Electric Vehicle
ARIMA: Auto Regressive Integrative Median Average
RMSF: Root Mean Squared Forecasting Error

1. Introduction

Carbon fiber reinforced polymers have been on the market for almost 60 years presenting a steady growth in its use; advances in carbon fiber production, manufacturing and mechanical design methodology together with the search of higher performance on products and machinery has resulted in economy scales and a reduction on the CFRPs cost and higher adoption.
Since 2020 under new goals for sustainability and the arising of new policies setting limits for the CO_2 production, CFRPs have showed their potential to substitute traditional materials and manufacturing techniques as a way to reduce weights and improve efficiencies in a wide range of industries.
Knowledge of the CFRP is mostly limited to highly specialized industry actors and academia; market research is also limited and opportunities are unknown for many engineering and manufacturing companies; therefore it is needed to compile high value information about CFRP technology not only for engineers but also for business people in a holistic way, identifying technology capacity, applications but also studying the current market and its forecasts.

1.1. Object

The object of the study here developed will be defined and described.

The general object of the project is the following:

To stablish a holistic view and analysis of the carbon fiber technology and market in a summarized way.

The general object can be divided into some specific objectives:

1. To search, filter and summarize key technology state of the art data
To stablish key CFRP technology data for engineers, designers and other readers, to review publications state of the art and generate accessible, holistic and summarized information.

2. To search, filter and summarize key market state of the art data
To stablish key CFRP market data for engineers, designers and other readers, to review publications state of the art and generate accessible, holistic and summarized information.

3. To produce analysis in CFRP market and technology
Key information will be analyzed in a quantitative and qualitative basis, conclusions will be drawn from the analysis

4. To analyze the environmental impact derived from CFRP use
To assess the environmental impact of the CFRP production, use and disposal, and to qualify and quantify the best methods for recycling.

5. To create a forecast for the CFRP market for the next 5 years.
To stablish most adequate forecasting techniques to predict the CFRP market and its behaviour during the following 5 years.

1.2. Scope

The scope of the project will be described, identifying the different work packages (WP) and deliverables that will configurate the study:

WP1. CFRP technology state of the art:
Technology state of the art study will cover CF internal structure and composition, the process for obtaining precursors and CF from them, the properties of carbon fibers and composites compared to the competing engineering materials, the study will also envelope the CFRP manufacturing processes and the methodology to design composite structures. The study will produce qualitative and quantitative analysis from the sourced data as well as conclusions.

WP2. CFRP market study
CFRP market study will treat the political and regulatory environment affecting CFRP adoption, the automotive, aerospace and energetic markets; the study will stablish the market drivers and barriers as well as the trends. Qualitative and quantitative analysis will be applied to the original publications to produce added value which will be summarized in conclusions.

WP3 CFRP environmental impact assessment:
CFRP environmental impact assessment will cover the Life Cycle Assessment (LCA) and recycling methods for CFRP. LCA will employ quantitative methods to measure CFRP impact in substitution of other materials during production, use, disposal and or recycling phases following ISO 14050:2006. Recycling methods study will compile the state of the art methods stablishing recovery grades, comparations, issues and future research fields.

WP4. CFRP market forecasting
A time series model will be employed to forecast carbon fibers sells in the period 2022-2027.

1.3. Limitations

Next, limitations and requirements of the study will be described:

WP1. CFRP technology state of the art.
· Study will be based on the existing literature review; experiments and characterization will not be carried out.
· Datasets for material characterization produced will compile open data from third parties, in a filtered and summarized way
· Materials analyzed will be limited to most common engineering materials and properties, values will be approximated
· For production methods study, only industrial, high capacity and high performance processes will be analyzed.
· Design methodology study will cover CLT theory, optimization methods and current software workflows focusing on inputs, outputs and limitations of the methodology, that is, black box approach, internal computing methods and theory will not be covered.

WP2. CFRP market study
· Study will be based on PESTLE (Political Economic, Sociological, Technological, Legal, Environmental) analysis.
· Strategic analysis reports and literature review will be employed as data sources.
· Market study will be focused on future market behavior and be qualitative.
· Study will cover aerospace, space, automotive and wind production industries.

WP3. CFRP environmental impact assessment:
· Study will be based on already produced data on environmental impact
· Quantitative analysis will be employed accounting for energy consumption and equivalent CO_2 eq quantities.
· For the study a standard automotive part will be employed in comparison versus steel.

WP4. CFRP market forecasting
· ARIMA Times series analysis methods will be employed.
· Studies will be based on historical sales data from manufacturers
· Forecast will cover a 5 year time period.

1.4. Rationale

Hereunder, the reasons to develop a study on CFRP technology and market are developed:

1. CFRP technological definition is currently atomized and is needed to compile key information in a single and holistic way.
Currently CFRP information is divided in multiple portals, books and publications, without critical mass in the academic and in the market to stablish CFRP as part of university curriculums.
CFRP technological definition involves the action of multiple classical disciplines such as chemistry, physics, mechanics, elasticity, materials engineering, design engineering, manufacturing or CAD/CAM/CAE.
It is needed to stablish the most important matter describing CFRP technology transversally and as a whole including precursors, characterization, manufacturing methods, applications and design methodology.

2. Current studies of CFRP market are private, opaque and limited in number and scope.
Current CFRP market analysis are mostly limited to private studies based on market intelligence software tools which show mainstream marketing metrics and basic qualitative analysis.
It is needed to produce free access data on the CFRP market exposing not only the market analysis but also the methodologies followed to produce it. This market analysis will also be centered in the EU market specific conditions and enhance classical market metrics with multivariate analysis . This market analysis will help industrial actors and researchers on decision making.

3. To arise consciousness about the environmental impact derived from CFRP use.
Despite the advantages and role of CFRPs as a facilitator to achieve higher efficiencies and lower carbon footprints during it is use, CFRPs have not achieved circularity presenting large footprints at their end of life. It is needed to analyze and diffuse the environmental impact of CFRP and identify the best practices to achieve circularity.

4. To develop filtered and quality datasets on CFRP market.
It is currently possible to find scattered data of the CFRP and carbon fiber markets as part of bigger studies becoming a time consuming and unproductive task.
There is a need to compile information from multiple sources which allows different actors for further analysis.

2. Background and review of state of the art.

The study here developed aims to produce new added value content based on the summary, relation, filtering and added content based on already developed literature.

Holistic CFRP and technology and market studies or similar will be enumerated next:

S.-J. Park on the book *Carbon Fibers* [1]: has produced a detailed study on CF and CFRP technology, the text in on the branch of materials science with focus on internal structure, chemical composition and treatment of the CF and CFRP materials. Despite treating CFRP applications, the book does not cover the CFRP market analysis. The book does not summarize information for the non-technical reader, which is one of the objectives of the study here developed.

J. Zhang, G. Lin, U. Vaidya, and H. Wang, "Past, present and future prospective of global carbon fibre composite developments and applications," [2]: The study covers technical and market aspects on CFRP, the work has been published very recently (1 February 2023), and to the date is the most similar work to the study here developed. Most significative differences are the following: The study does not cover the PESTLE analysis for the market study or environmental impact study, it does not apply time series forecasting techniques, length is limited due to the scientific literature character. It is important to highlight that many of the conclusions of the study developed on this master thesis agrees with the contents of this publications.

Other studies developed are atomized on different branches and fields, and are specialized on different topics such as manufacturing, design methodology, LCA, etc. These studies are not considered as state of the art for the content developed in this master thesis as they are not comprehensive/overview studies; this publications are exposed through the work and are included as bibliographic references.

3. Methodology

WP1. CFRP technology state of the art:

· In first place, the key information for CFRP technological analysis will be defined.
· A search of relevant information will be performed among scientific publication databases and books.
· Data will be filtered to match the key information needed in a summarized way and will be integrated for its comprehension.
· Qualitative and quantitative analysis will be performed.
· Data visualization tools will be employed to facilitate analysis and comprehension.
· Conclusions based on the qualitative, quantitative and graphical analysis will be extracted.

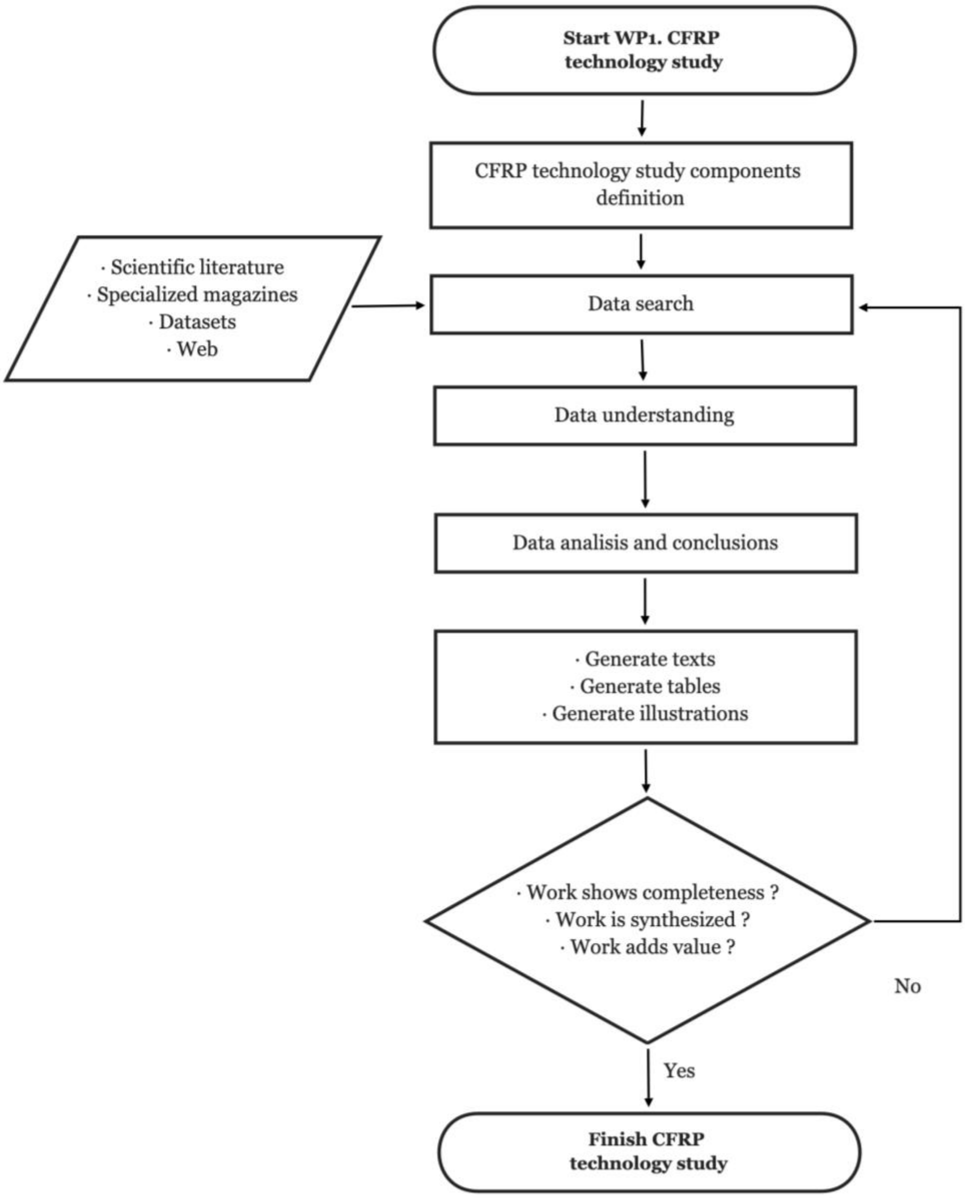


Fig. 1. WP1 CFRP technology study methodology

WP2. CFRP recyclability methods and life cycle assessment:
· An average case of CFRP production will be selected.
· An LCA analysis based on ISO 14040:2006 will be performed
· Recycling methods will be studied, compiled and analyzed
· Conclusions and decisions on environmental impact will be thrown.

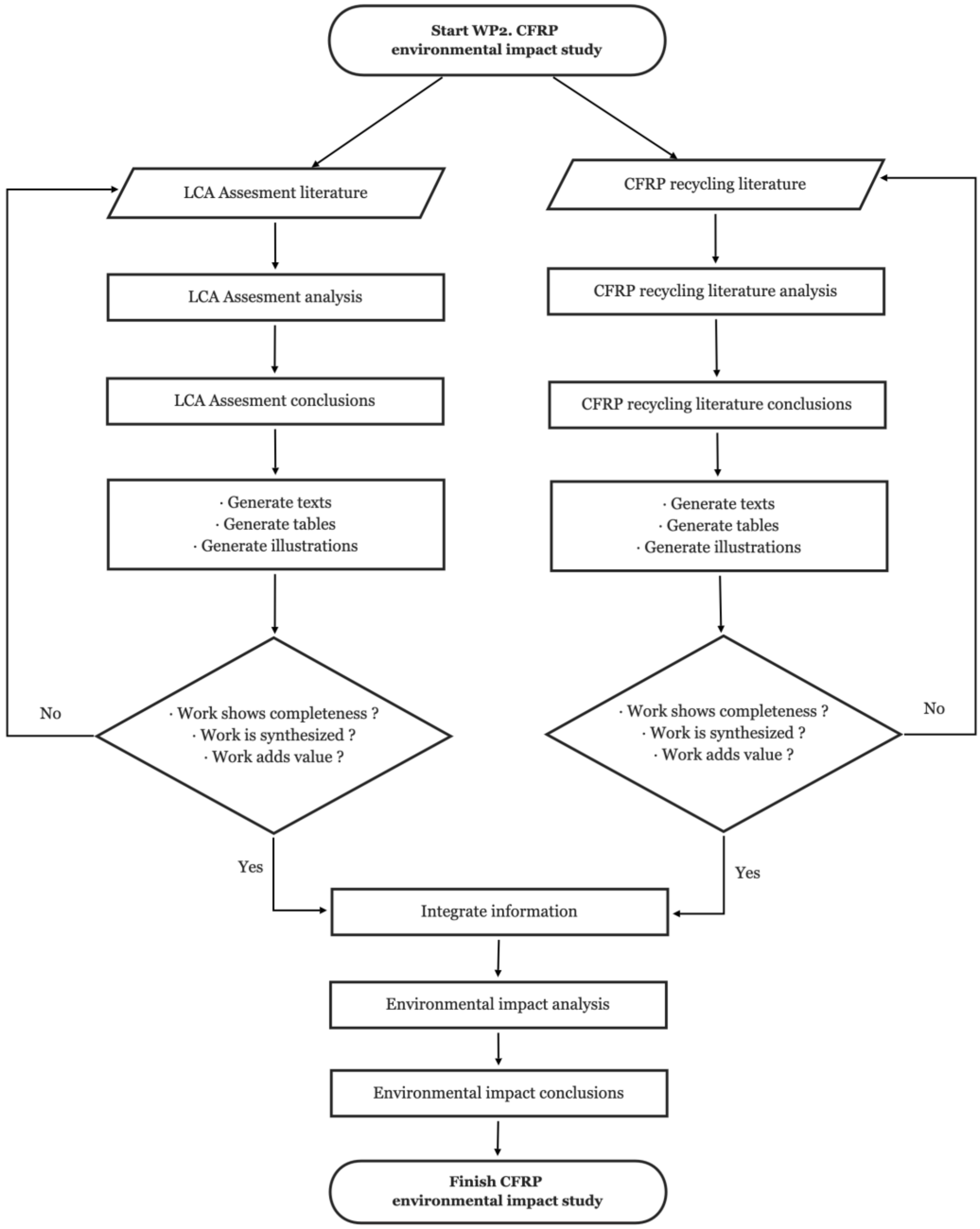


Fig. 2. CFRP environmental impact study

WP3. CFRP market study

· In first place, the key information for CFRP market analysis will be defined.

· A search of relevant information will be performed among scientific publication, public organizations, public databases and strategy consultancy firms

· Data will be filtered to match the key information needed in a summarized way and will be integrated for its comprehension.

· Qualitative and quantitative analysis will be performed to relate concepts. Multivariate analysis techniques will also be employed.

· Data visualization tools will be employed to facilitate analysis and comprehension.

· Conclusions based on the qualitative, quantitative and graphical analysis will be extracted.

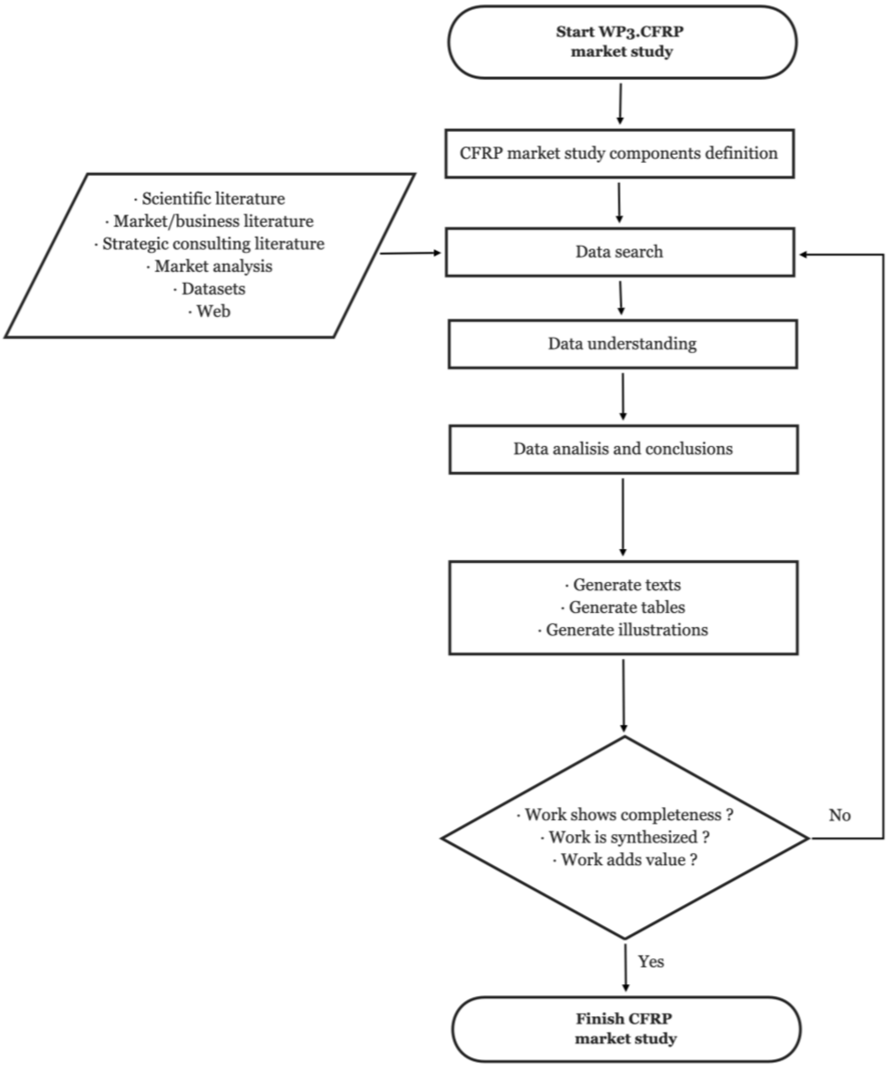


Fig. 3. WP3 CFRP market study methodology

WP4. Time series forecast of the CFRP market.

· Key information to forecast will be defined.

· Multiple times series forecasting techniques will be employed, quality of the fitting will be the main driver for model selection.

· A forecast will be produced for years 2022-2027

Fig. 4. CFRP market forecast methodology

3. CFRP technology study

3.1. Introduction to CFRP technology study

To the date, CFRP materials have been characterized in the field of materials engineering and science; literature has covered the carbon fiber characterization, describing carbon molecular and crystalline forms; the carbon fiber internal structure and the carbonization process from PAN, pitch and other precursor fibers.

Compatibility between carbon fibers and the polymeric matrices have been studied as well, stablishing the theory in the bond between materials and its improvement through sizing and surface treatment.

Resulting carbon fibers have been characterized mechanically; stablishing guidelines for measuring not only mechanical properties but assessing the structure of this relatively new material; manufacturing processes have been studied as well, different authors propose different classifications of the process and criteria on manufacturing selection.

The aim of the technology study is to offer a general view for the designers point of view, that is, focusing on mechanical and technical characteristics, manufacturing, design and with a special focus on the environmental problem CFRP materials imply.
Novelty of the study will then be hold on:
· The point of view of the research (design engineering focus)
· Material properties for CF and CFRP will not be limited to mechanical but to general technical properties.
· It will also create an open access dataset compiling core engineering properties of CFRPs and other competing materials
· The addition of quantitative and qualitative analysis supported by state of the art data visualization techniques
· A high level explanation on the CFRP mechanical design methodology,
· The guidance on decision making on manufacturing processes
· The analysis of environmental aspect of CFRP design and use

Among the outstanding technical properties and the flexibility on manufacturing; CFRP materials find their weakness in the environmental aspect, surprisingly, as has happened with other technologies such as electrical batteries for EVs, CFRP materials are both a solution and an environmental problem if lifecycle is not planned. The study will cover the recycling problem and will quantify environmental effects through LCA assessment.

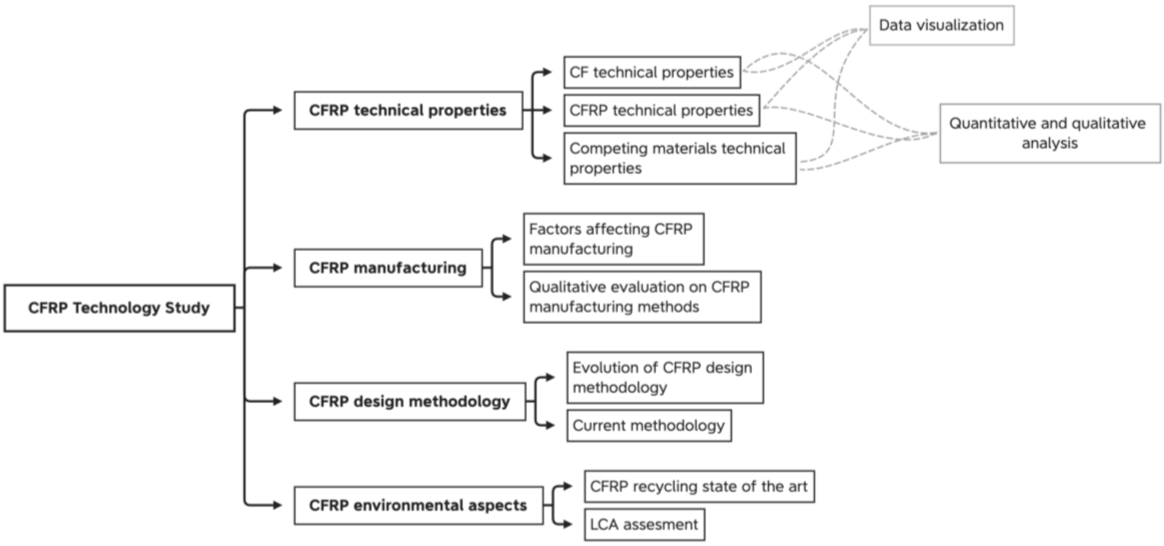


Fig. 5. Structure and parts of the CFRP technology study

3.2. CFRP technical properties

3.2.1. Introduction to CFRP technical properties

In this chapter, focus will be hold on the quantitative and qualitative analysis on CFRP materials, offering comparisons with other engineering materials expanding the mechanical with other engineering properties.

Data of different technical characteristics will be compiled from different sources on a dataset, taking into account mechanical, thermal, electrical, and cost fields; then, it will be filtered and plotted as to facilitate analysis by non- experts on material science.

3.2.2. Basic information of carbon fibers

Carbon Fiber definition:

Works from Soo-Jin Park [1] compile the definition of carbon structures, covering the molecular and crystalline forms (allotropes) of carbon; the wide definition of carbon fibers, their classification based on performance; the manufacturing of carbon fibers from precursors and the graphitization process as well as the different precursors composition and technical characterization of carbon fibers characteristics.

Carbon fibers are then, well characterized from a chemical and physical point of view by the works on the field of material science.

Hereafter a short definition of carbon fibers is given.

Carbon Fiber: Synthetic fiber constituted by thin cylindrical filaments of 6-10 µm of diameter, being chemically constituted by at least 93-95% carbon, characterized by high modulus of elasticity and low density.

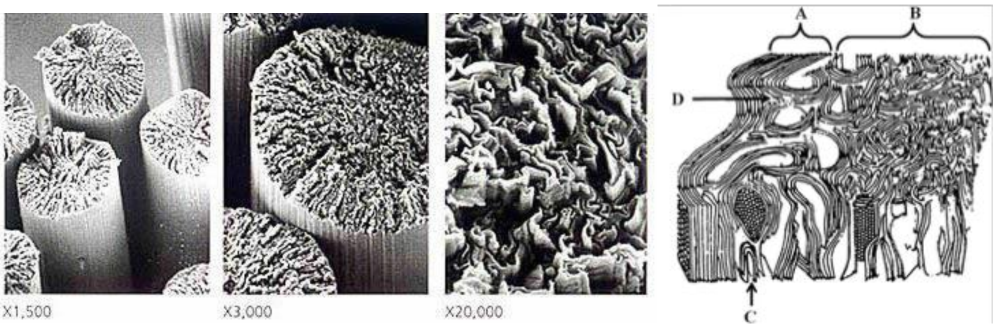


Fig. 6. Microscope cross section of carbon fibers, defects on carbon fibers [1]

Carbon fibers are obtained by the graphitization of the precursor fibers.

<u>Precursor fibers:</u>
Carbon fibers are commonly obtained from the graphitization process of PAN (polyacrylonytrile) or pitch based fibers (precursors)

PAN based precursor fibers are obtained by the polymerization of acrylonitrile (a petrochemical product), PAN co-polymer needs to be spinned to form the fibers, to produce the spinning, DMSO (Dimethyl sulfoxide) is commonly employed. To produce carbon fiber PAN based precursor fibers are carbonized by heat without oxygen.

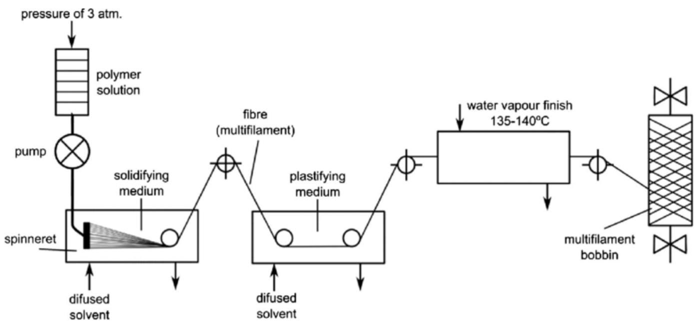


Fig. 7. Schematic diagram of the spinning process of PAN fibres.[3]

Pitch based precursor fibers are obtained from pitch (undistillable products); process for obtention of pitch based fibers is similar to PAN but the latter exposes problems in the spinning process because of PAN stiffness to produce fibers.

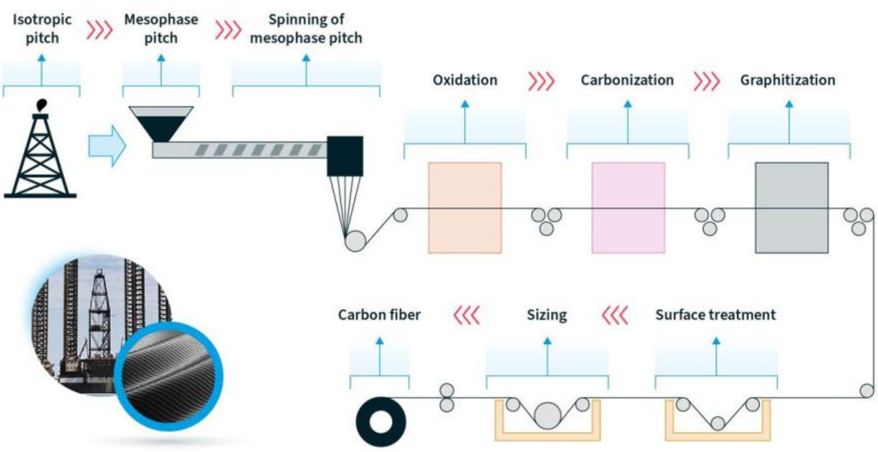


Fig. 8. Schematic diagram of the spinning process of pitch based carbon fibers[4]

PAN based carbon fibers hold a strong position in worldwide fiber market (95% of total carbon fiber produced).

Complexity on pitch based fibers manufacturing process has been exposed by Soo-Jin Park [1] multiple publications highlight the challenge on the melt spinning process that pitch fibers imply [5] [6] [7].

Graphitization process:
Precursor fibers are submitted to oxidization (heat with oxygen) and carbonization (heat on inert gas) processes to eliminate non carbon-elements and defects, the result is a tightly packaged structure containing no less than 93% carbon and graphitic crystal structure.

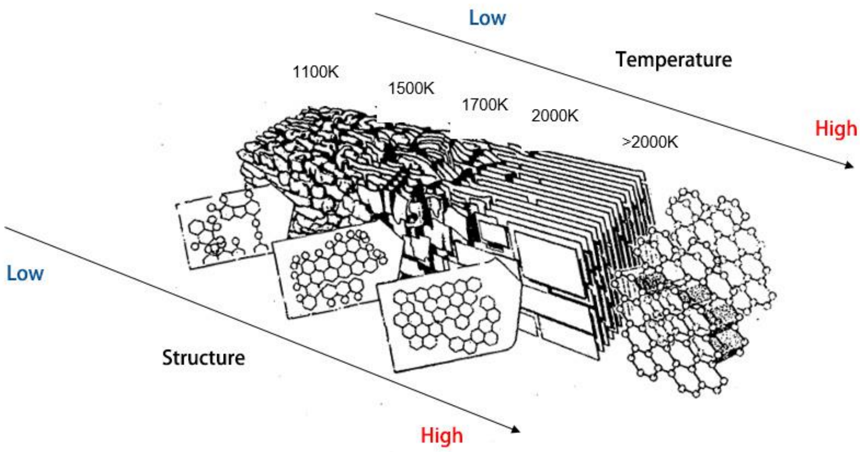


Fig. 9. Structural model for carbon fibers during graphitization process [8]

3.2.3. CF and composites technical properties

In this chapter, general technical data will be compiled for fibers, CFRP and other substitute/competing engineering materials. Qualitative and quantitative analysis will be done together with technical characteristics visualization to facilitate the reader's comprehension.

Technical properties datasets:
Based on multiple sources, multiple datasets have been generated for CF, competing fibers, common and CFRP composites and other engineering materials; those datasets and sources references can be found on *Annex I. Data tables.* and constitute part of this thesis work and objectives.

CF and CFRP Norms:
For the definition of technical properties, CFRP materials are subject to specific testing; next different procedures employed are enumerated and resumed:

(ISO 10618:2004) Determination of tensile properties of resin-impregnated yarn:
A yarn sample is impregnated uniformly with resin, and then, it is polymerized to obtain probes, probes are submitted to tensile loads until failure.

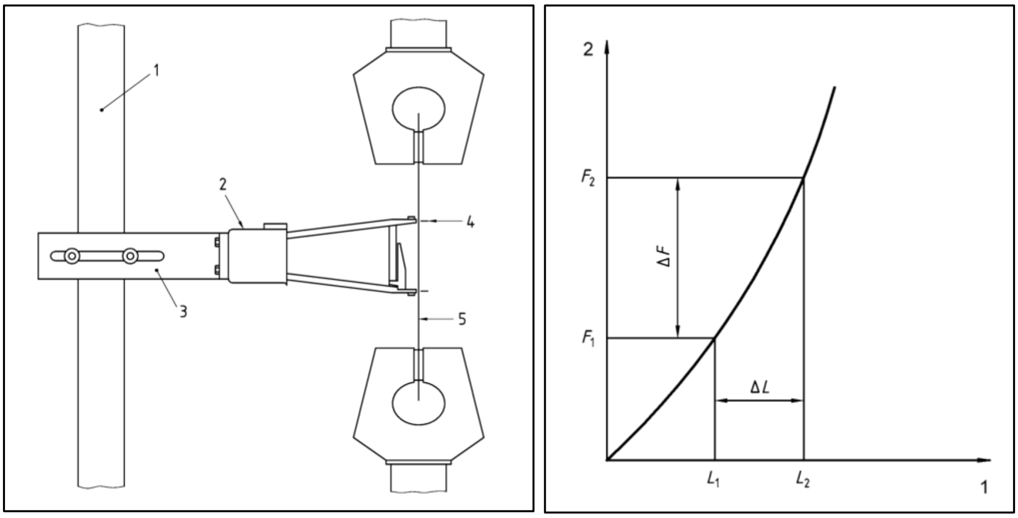


Fig. 10. Deformation machine and force-displacement curve. ISO 10618:2004

(ASTM D 3039/D) Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials:

A thin flap strip of material with constant rectangular cross section is subject to progressive and uniform increment of tension while recording load. Ultimate strength of the material is determined from the maximum load carried before failure.

If the material is monitored with strain or displacement transducers then the stress-strain response can be determined from which the ultimate tensile strain, tensile modulus of elasticity or Poisson's ratio, and transition strain can be derived.

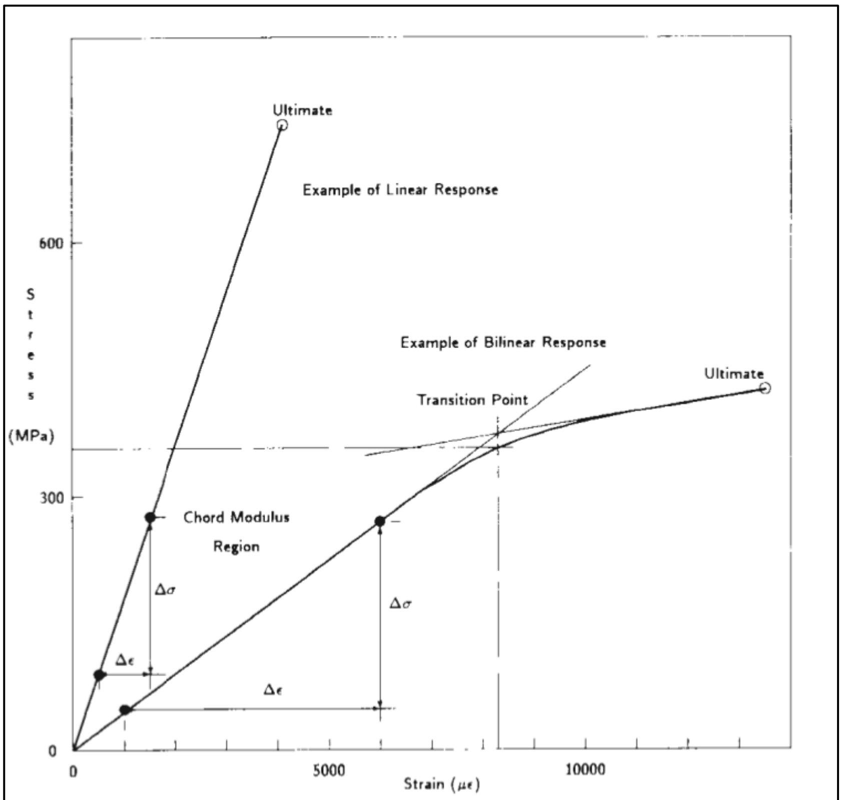
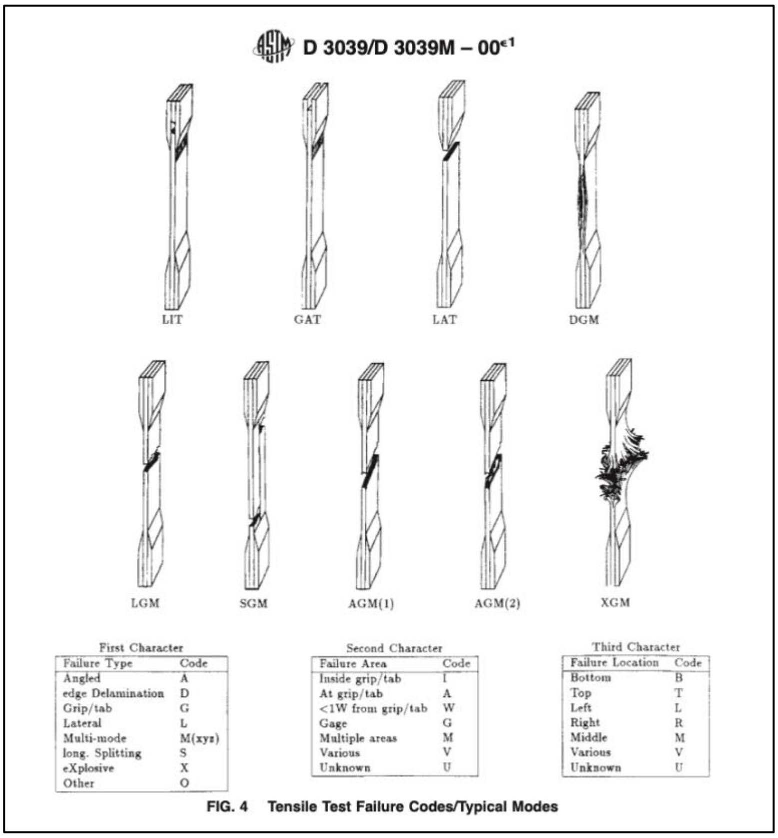


FIG. 5 Typical Tensile Stress-Strain Curves

Fig. 11. Tensile test stress-strain curve and fracture codes. ASTM D 3039/D


D 3039/D 3039M – 00ε1

LIT GAT LAT DGM

LGM SGM AGM(1) AGM(2) XGM

First Character

Failure Type	Code
Angled	A
edge Delamination	D
Grip/tab	G
Lateral	L
Multi-mode	M(xyz)
long. Splitting	S
eXplosive	X
Other	O

Second Character

Failure Area	Code
Inside grip/tab	I
At grip/tab	A
<1W from grip/tab	W
Gage	G
Multiple areas	M
Various	V
Unknown	U

Third Character

Failure Location	Code
Bottom	B
Top	T
Left	L
Right	R
Middle	M
Various	V
Unknown	U

FIG. 4 Tensile Test Failure Codes/Typical Modes

Fig. 12. Typical failure modes and codes of composite materials. ASTM D 3039/D

This standard will be employed to define CFRP tensile strength.

(ASTM D790) Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials:

A test specimen of rectangular cross section rests on two supports in a flat-wise position and is loaded by means of a loading nose located midway the supports. The specimen is deflected until rupture occurs in the outer surface or until a maximum strain of 5.0% is reached, whichever occurs first.

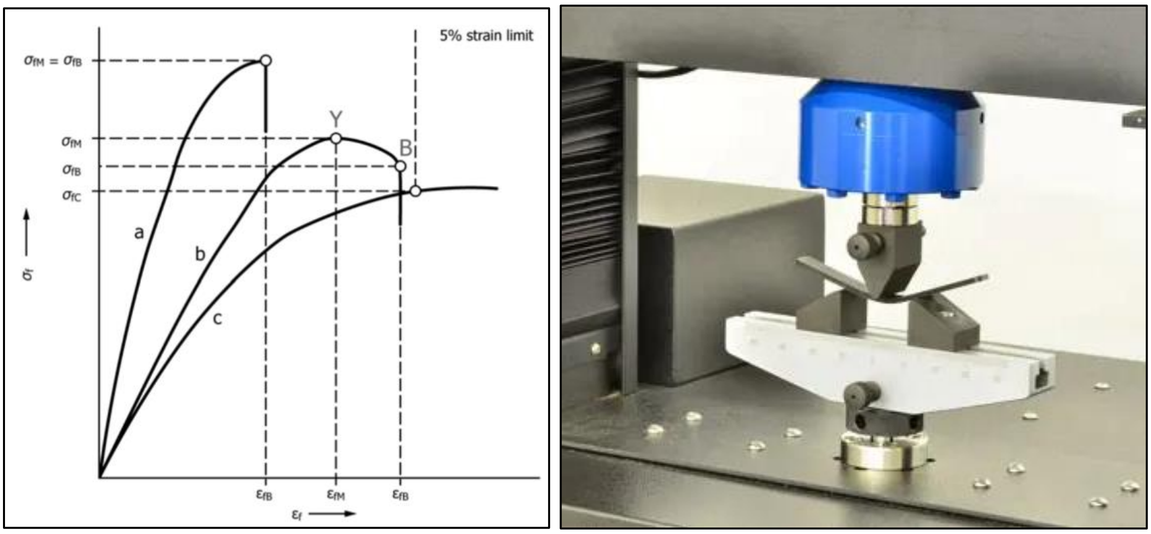


Fig. 13. Typical curves of flexural stress. ASTM D790

This standard will be employed to define CFRP flexural strength.

(ASTM D 3518) Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a +-45º Laminate:

A uniaxial tension test of a +-45º laminate is performed in accordance with Test Method D3039, although with specific restriction on stacking sequence and thickness.

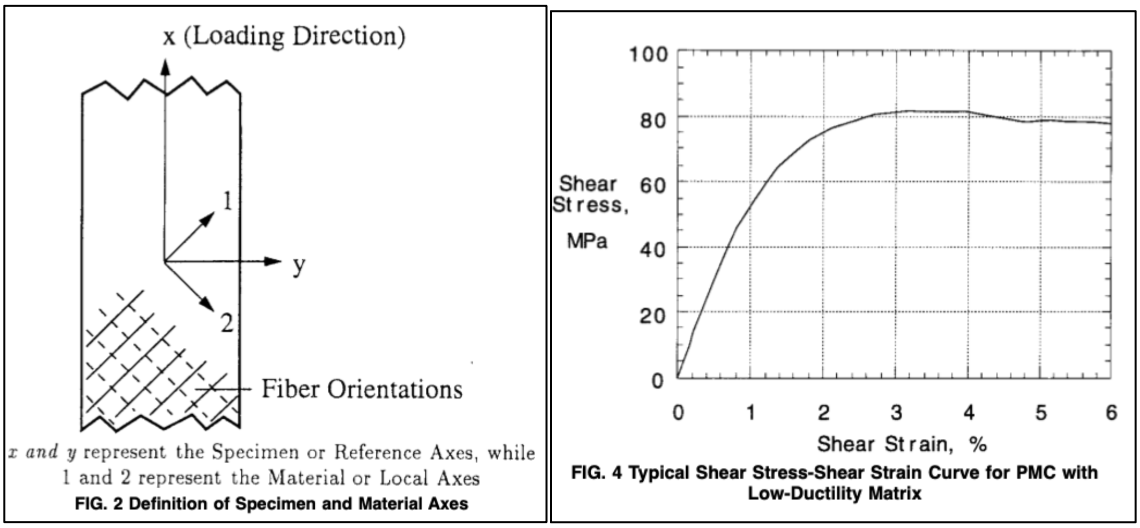


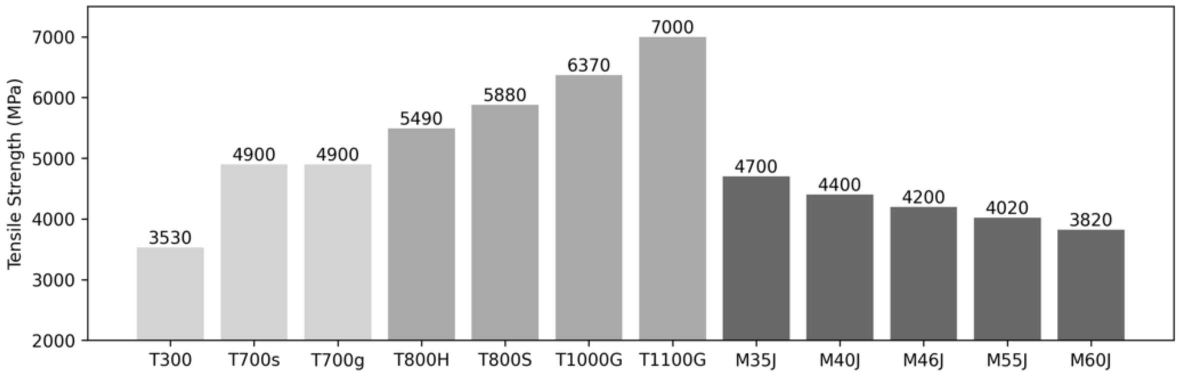
Fig. 14. Specimen and material axes and stress-shear curve. ASTM D 3518

The standard will be employed in cases of delamination of CFRP.

<u>Carbon fibers technical properties:</u>

<u>Univariate analysis:</u>

Following graphics show the technical properties of different grades of carbon fibers produced by TORAY Industries.



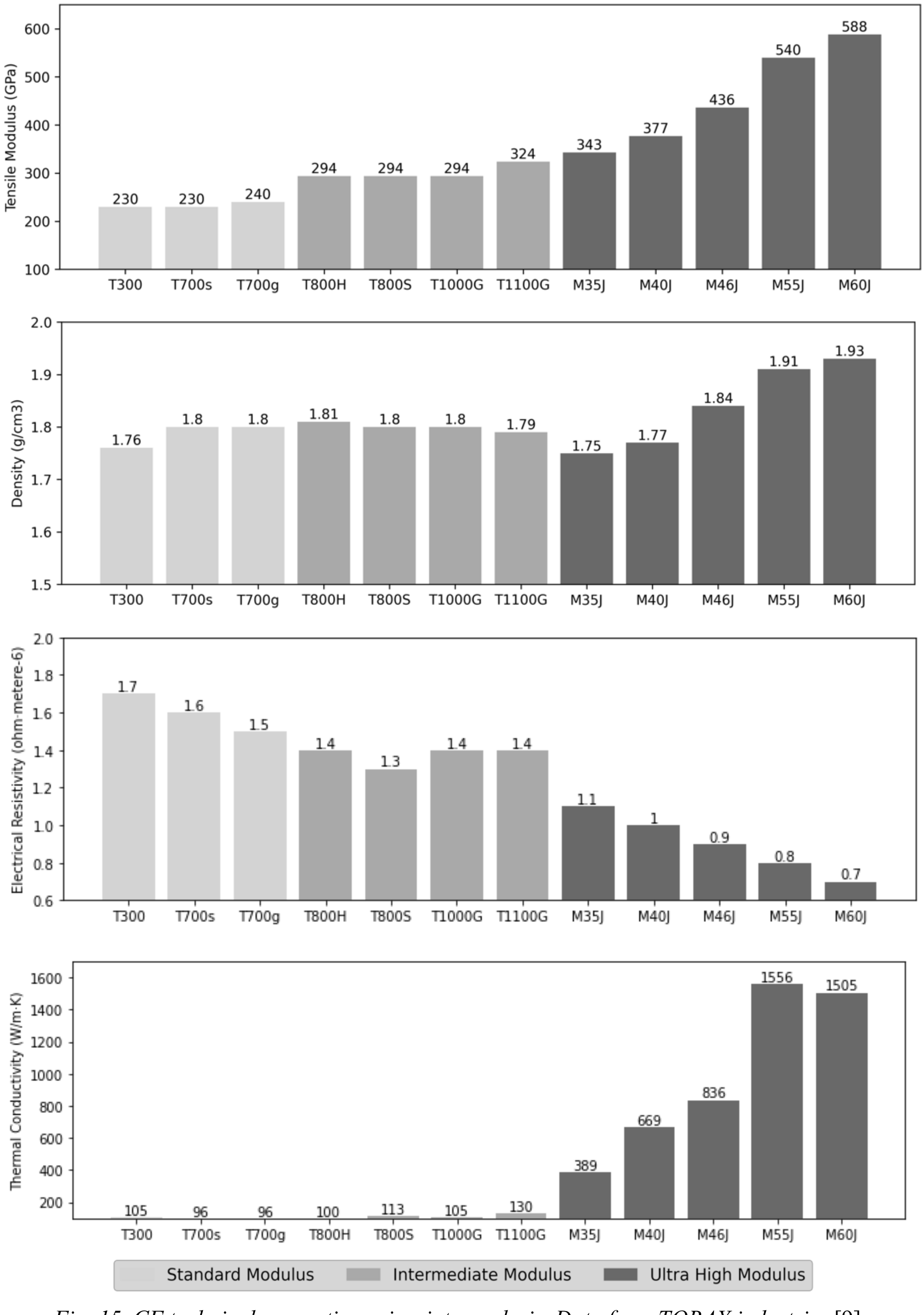


Fig. 15. CF technical properties univariate analysis. Data from TORAY industries.[9]

It is important to note the exceptional tensile strength and modulus values; low overall density, low resistivity and good thermal conductivity; these characteristics are unsurprising when taking into account the high carbon content and the level of packing produced by the crystalline structure.

Multivariate analysis:

Multivariate analysis makes sense when looking at the carbon content; as carbon content increases tensile modulus does, tensile strength drops because of the increment of rigidity which produces fragile failure.

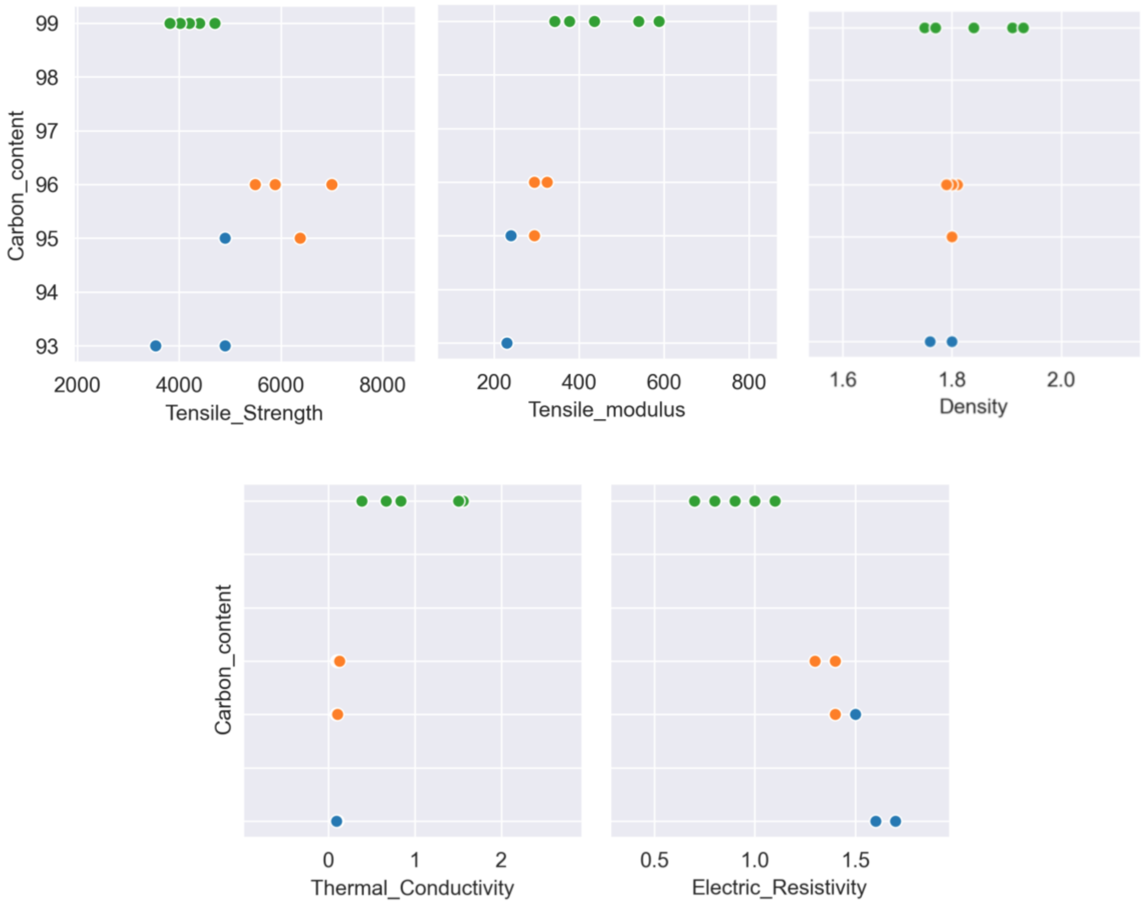


Fig. 16. CF technical properties multivariate analysis. Data from TORAY industries.[9]

Carbon content is directly related to thermal conductivity and has inverse relation with electrical resistivity.

Plotting tensile modulus versus tensile strength is also interesting, it can be seen that pitch based carbon fibers are the most rigid ones, exceeding in modulus but with fragile failure as high modulus PAN based fibers.

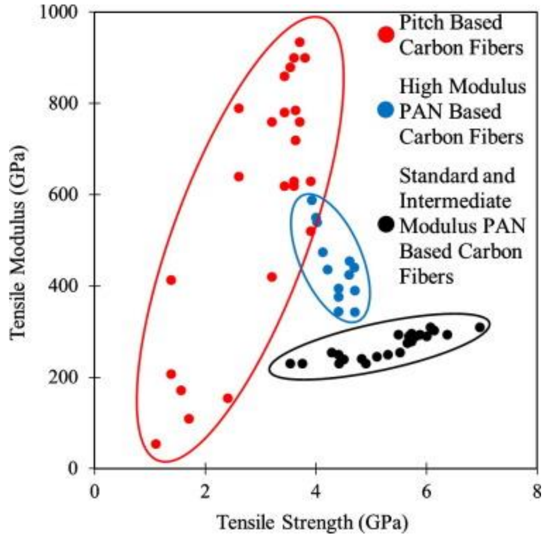
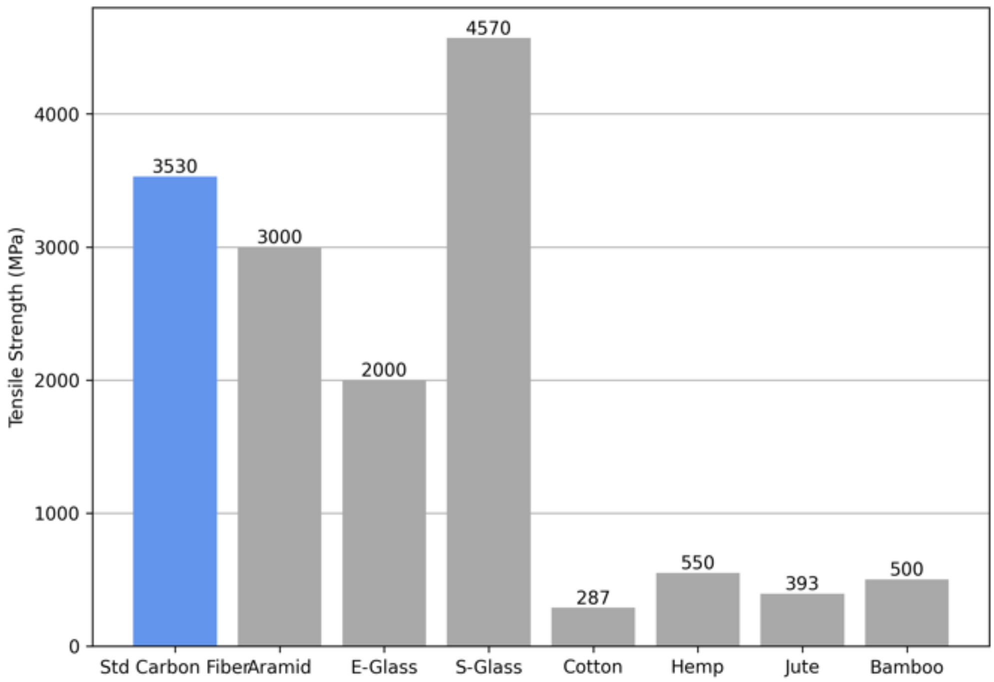
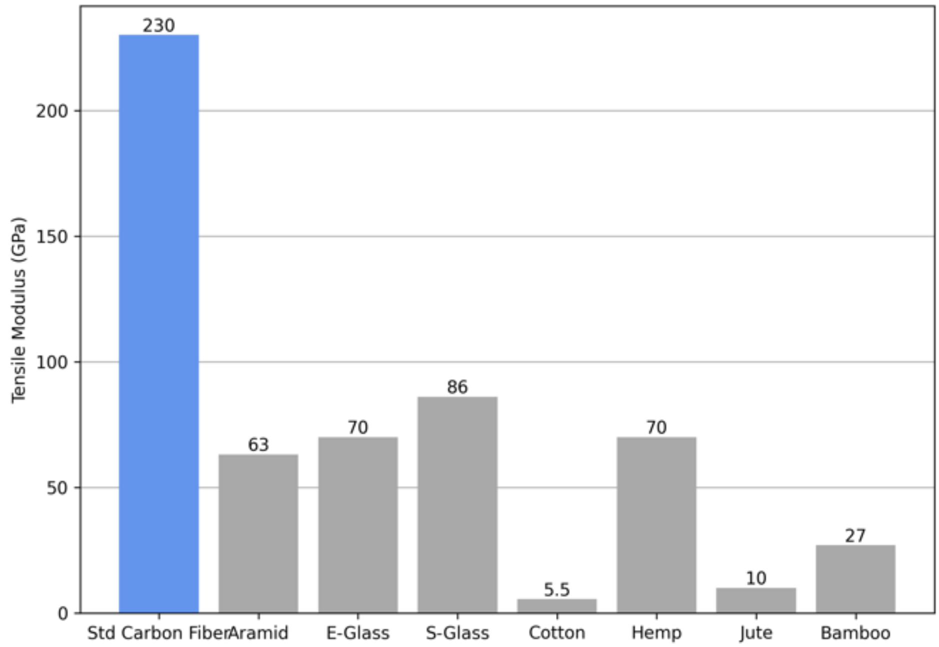
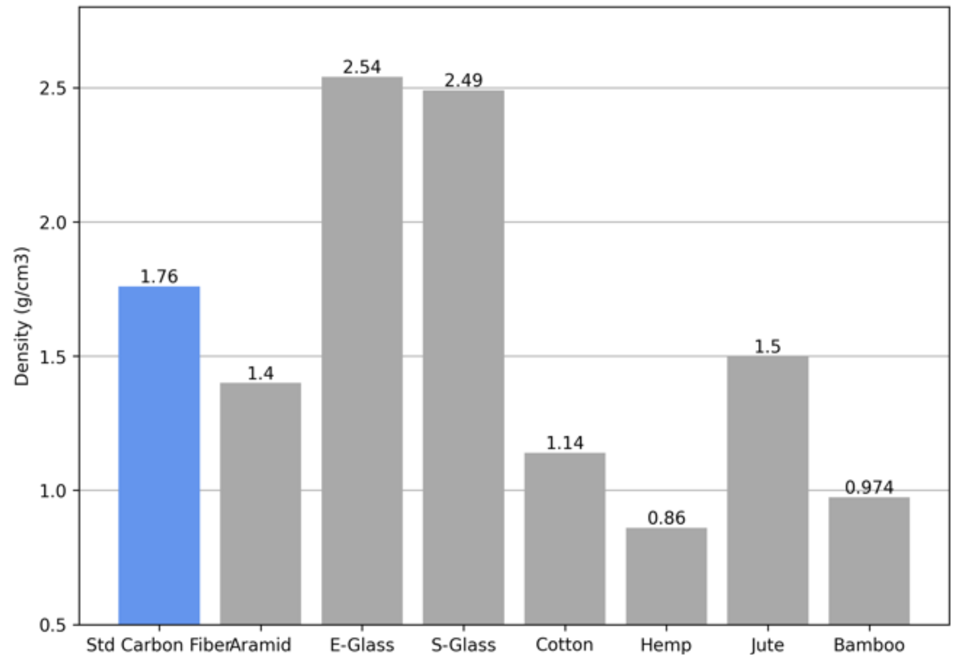


Fig. 17. Tensile modulus and strength of different grade and precursor carbon fibers. [10]

<u>Other fibers technical properties:</u>
Next graphics will compare the standard carbon fiber technical properties with other fibers data.




Tensile Modulus (GPa)
230
63
70
86
5.5
70
10
27
Std Carbon Fiber
Aramid
E-Glass
S-Glass
Cotton
Hemp
Jute
Bamboo


Density (g/cm3)
1.76
1.4
2.54
2.49
1.14
0.86
1.5
0.974
Std Carbon Fiber
Aramid
E-Glass
S-Glass
Cotton
Hemp
Jute
Bamboo

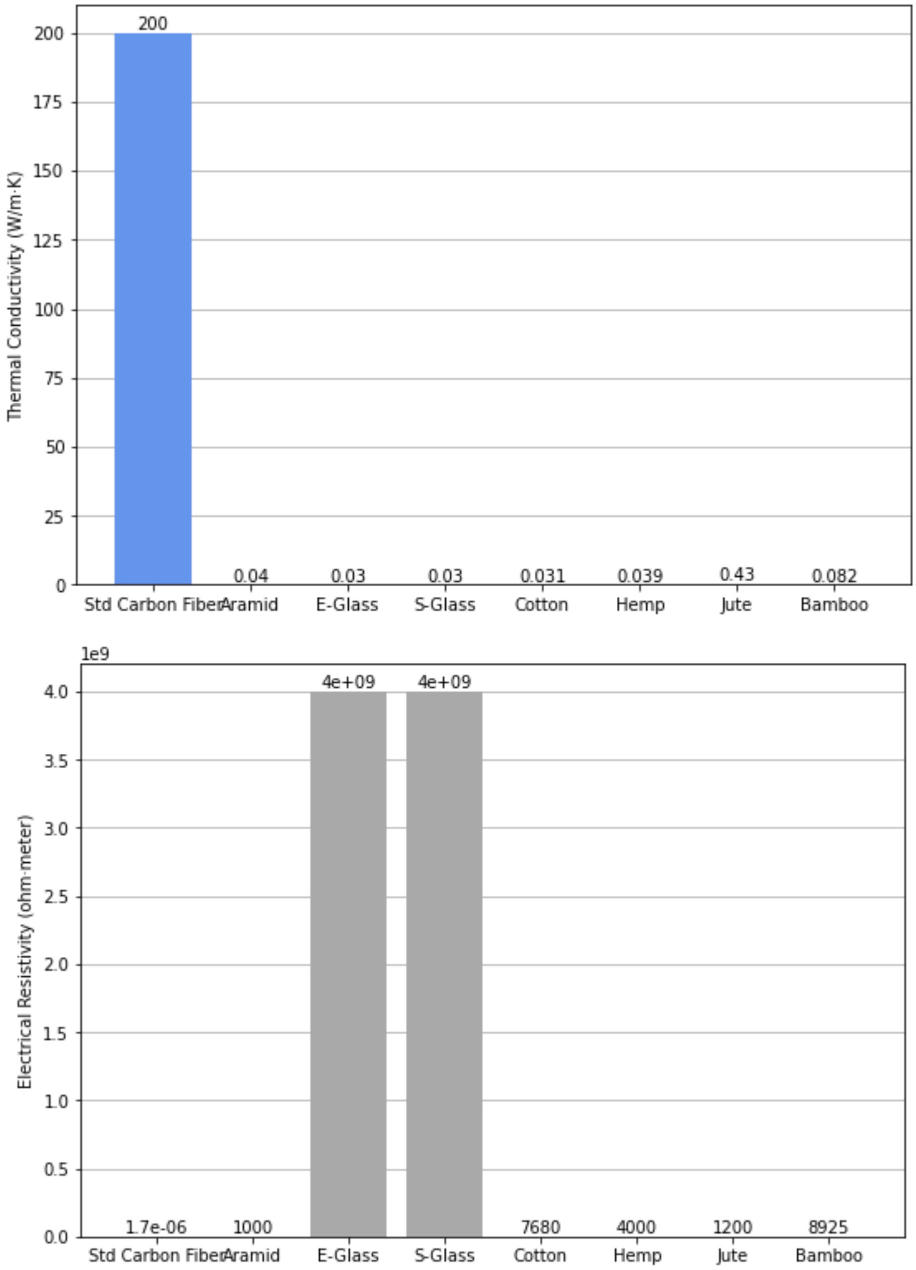


Fig. 18. Common engineering fibers technical properties.

In terms of mechanical performance, the only materials close to carbon fibers are E-Glass (Electric or standard glass fibers) and S-Glass (High performance glass fibers); which exhibit similar technical strength but lower modulus and also share manufacturing methods. Tensile modulus shows that glass fibers are a third less rigid than CF.

However, glass fiber prices are about a tenth part than carbon's and that makes them suitable for applications with lower performance or rigidity needs.

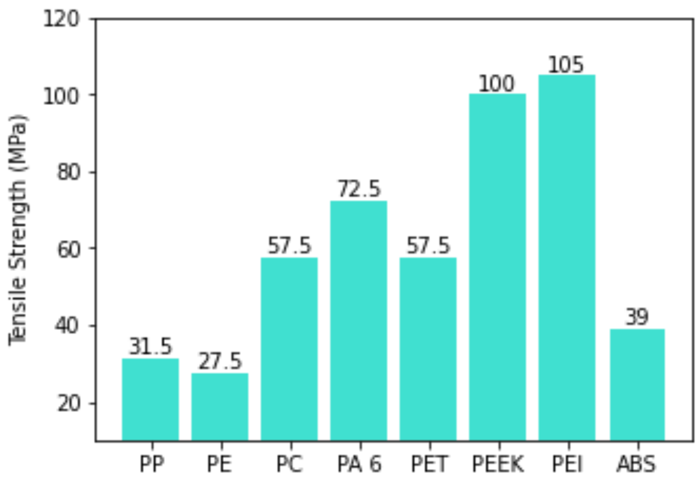
Another material which exhibits similar characteristics to carbon is aramid, aramid is a heat-resistant and strong synthetic fiber, an aromatic polyamide with high performance under with defense and military applications. Aramid has even less density than carbon fibers and can be produced with similar methods on thermoset and thermoplastic matrices. Despite having high tensile strength, modulus is low as four times lower than CF. Aramid fiber cost are around 80% higher than CF; and its use has added value when treating abrasion resistance.

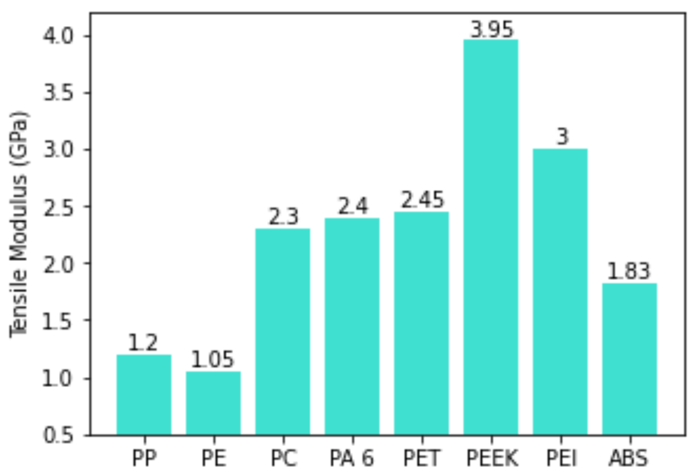
Natural fibers are well far from a mechanical perspective, latest developments are in carbonization processes applied to natural fibers to increase their carbon contents.

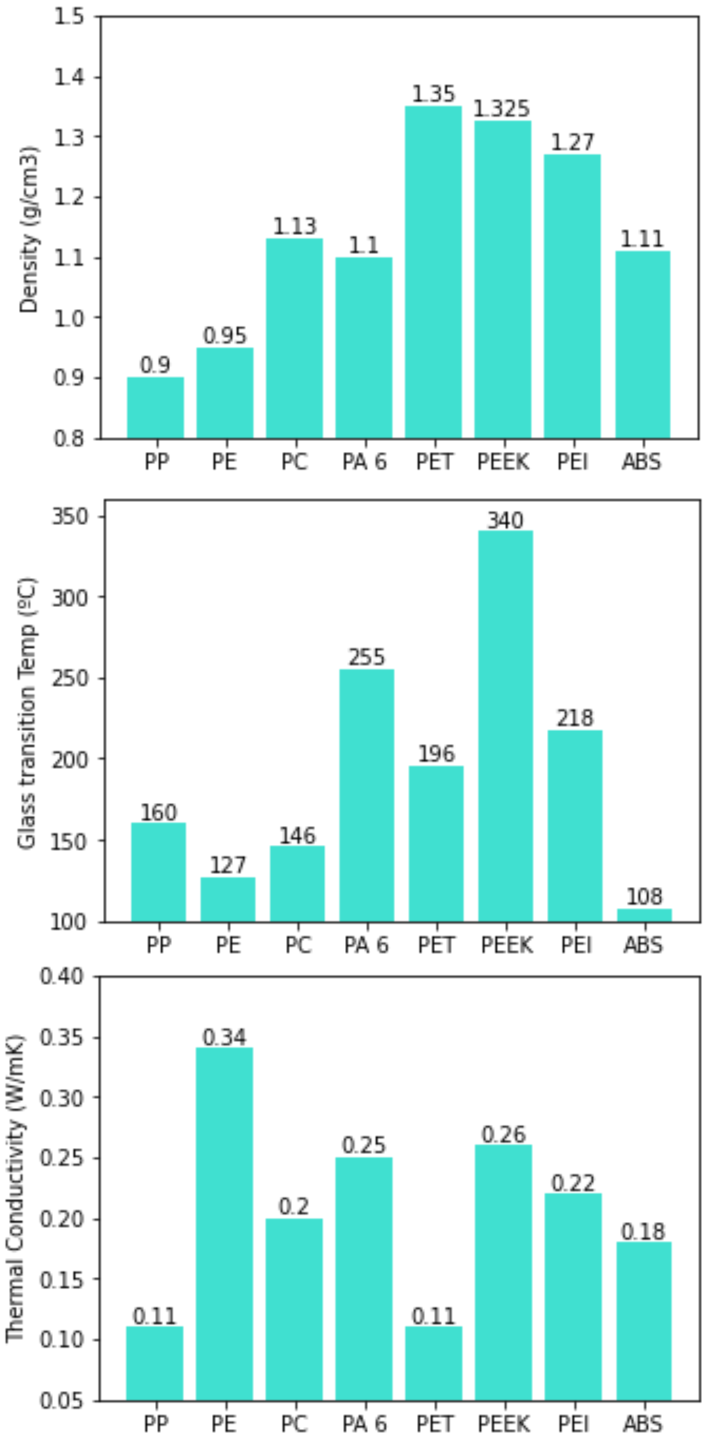
Polymeric matrices technical properties:
As most of the CFRP matrices are polymers, either thermoset or thermoplastic, it makes sense to make comparisons between both in order to understand performance factors.
It must be taken into account that currently, highest mechanical compatibility and adhesion between carbon fiber and matrix is achieved through thermosets that allow flowing around fibers and the later curing.

Thermoplastic material properties:
Thermoplastic mechanical properties are around 50 times less resistant to tensile and rigid than CF. Being most of them highly isolating materials electrically and thermally. Among thermoplastics, PC and PA 6 exhibit highest performance being standard market materials, other plastics that have been developed as high performance materials are PEEK and PEI which double mechanical characteristics of other thermos plastics.

One important factor when employing plastics is the glass transition temperature, at which critical loss of mechanical strength is produced; this temperature is critical on certain parts of the automobiles or space vehicles. Is in these temperatures that PEEK and PEI outperform other plastics.






Density (g/cm3)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.9
0.95
1.13
1.1
1.35
1.325
1.27
1.11
PP
PE
PC
PA 6
PET
PEEK
PEI
ABS
Glass transition Temp (ºC)
350
300
250
200
150
100
160
127
146
255
196
340
218
108
PP
PE
PC
PA 6
PET
PEEK
PEI
ABS
Thermal Conductivity (W/mK)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.11
0.34
0.2
0.25
0.11
0.26
0.22
0.18
PP
PE
PC
PA 6
PET
PEEK
PEI
ABS

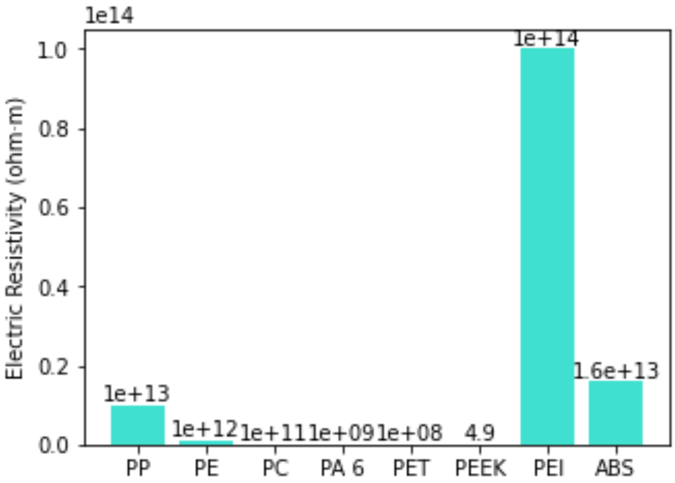
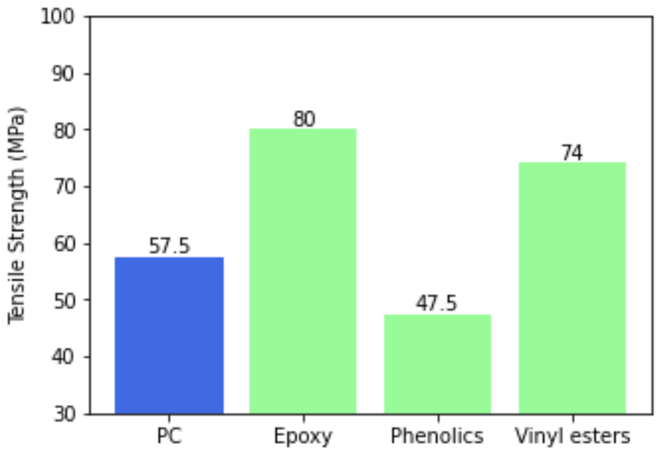
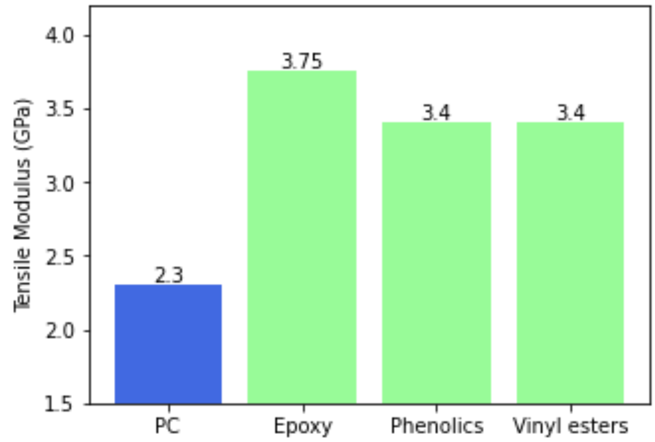


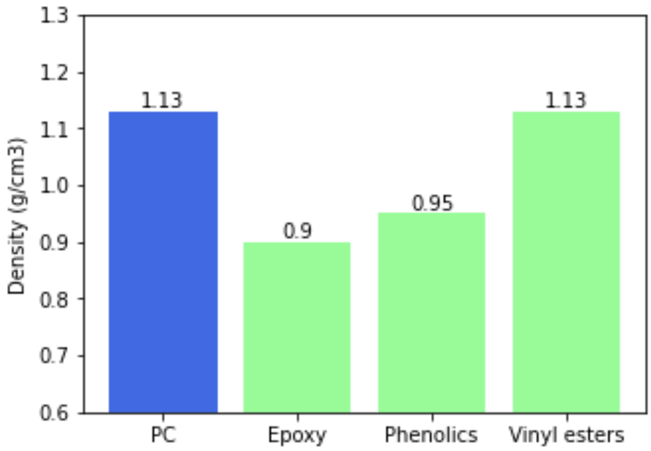
Fig. 19. Thermoplastic materials technical properties

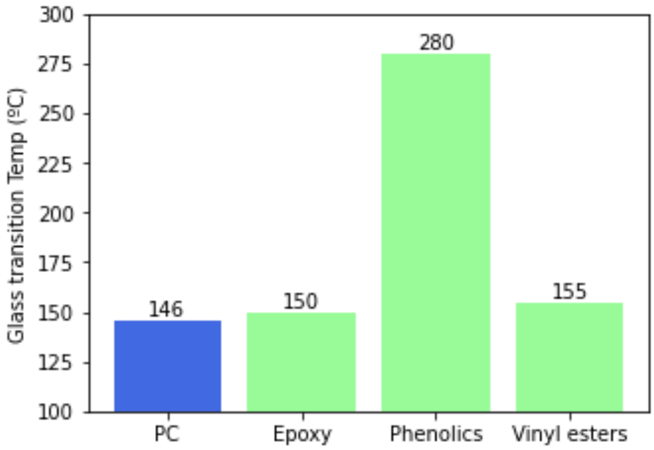
<u>Thermoset material properties:</u>
Following figures illustrate most common thermoset material properties versus PC taken as a standard thermoplastic. Thermoset materials are characterized by the 3D links produced on the chains when curing, this characteristics allows thermosets to be more resistant to traction and rigid, exhibiting around 1,5 times more mechanical performance than thermoplastics.

Epoxy resins, the most frequent matrix for carbon fiber exhibits one of the highest mechanical performance in plastics; phenolics, although less rigid, can become useful in temperature critical applications.




Tensile Modulus (GPa)
4.0
3.5
3.0
2.5
2.0
1.5
3.75
3.4
3.4
2.3
PC
Epoxy
Phenolics
Vinyl esters


Density (g/cm3)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
1.13
0.9
0.95
1.13
PC
Epoxy
Phenolics
Vinyl esters


Glass transition Temp (ºC)
300
275
250
225
200
175
150
125
100
146
150
280
155
PC
Epoxy
Phenolics
Vinyl esters

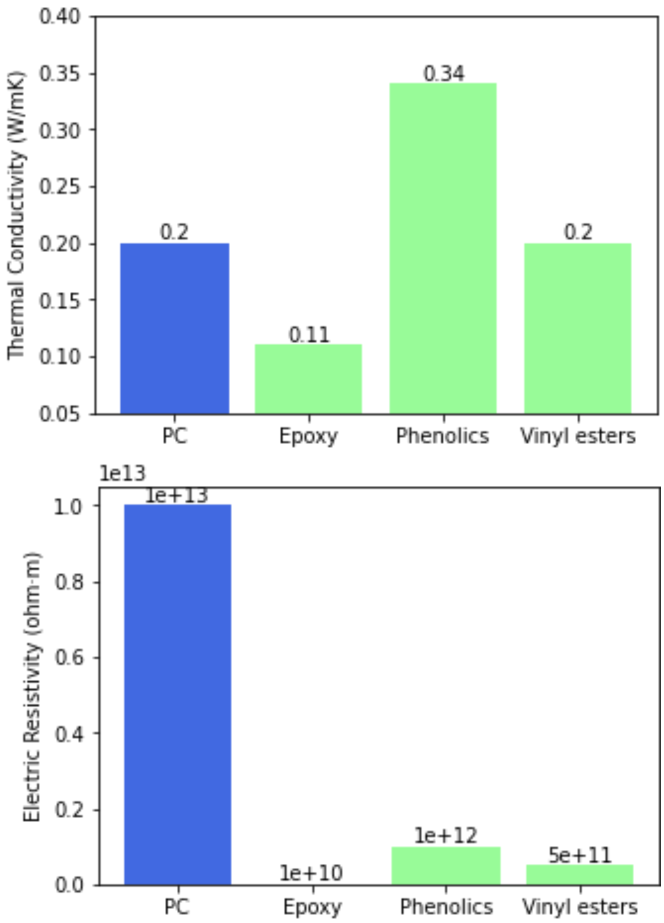
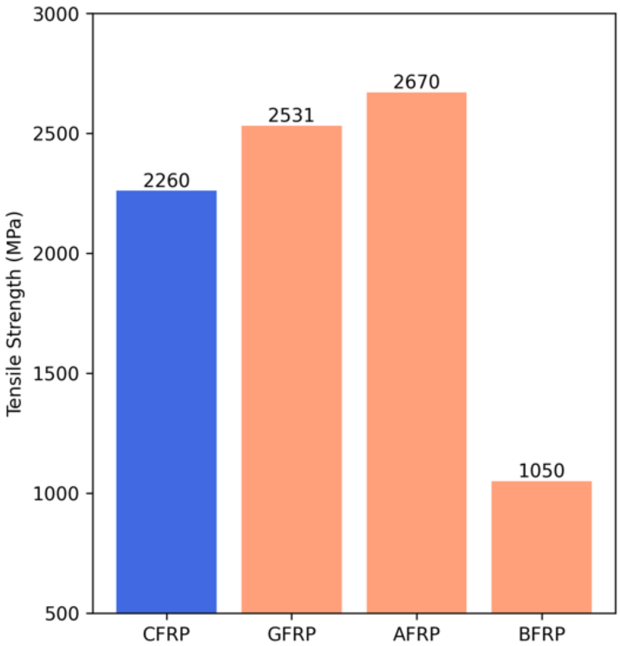
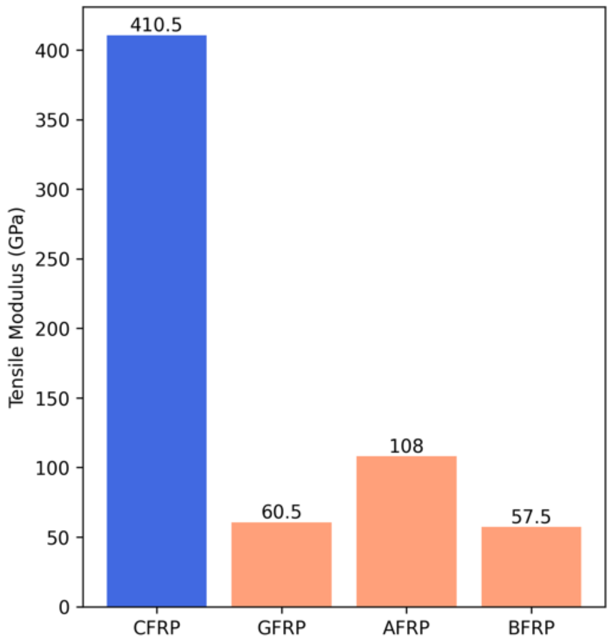


Fig. 20. Thermoset materials technical properties

Composites materials technical properties:

The following graphics will exhibit technical properties of CFRP produced from the TORAY carbon fibers and other reinforced materials.
On the following graphics; CFRP data is based on Standard Carbon Fibers form TORAY on a 2500 epoxy matrix normalized at 60% fiber volume.
GFRP stands for Glass Fiber Reinforced Plastic employing S-Glass
AFRP stands for Aramid Fiber Reinforced Plastic
BFRP stands for Basalt Fiber Reinforced Plastics


Tensile Strength (MPa)
3000
2500
2000
1500
1000
500
2260
2531
2670
1050
CFRP
GFRP
AFRP
BFRP


Tensile Modulus (GPa)
400
350
300
250
200
150
100
50
0
410.5
60.5
108
57.5
CFRP
GFRP
AFRP
BFRP

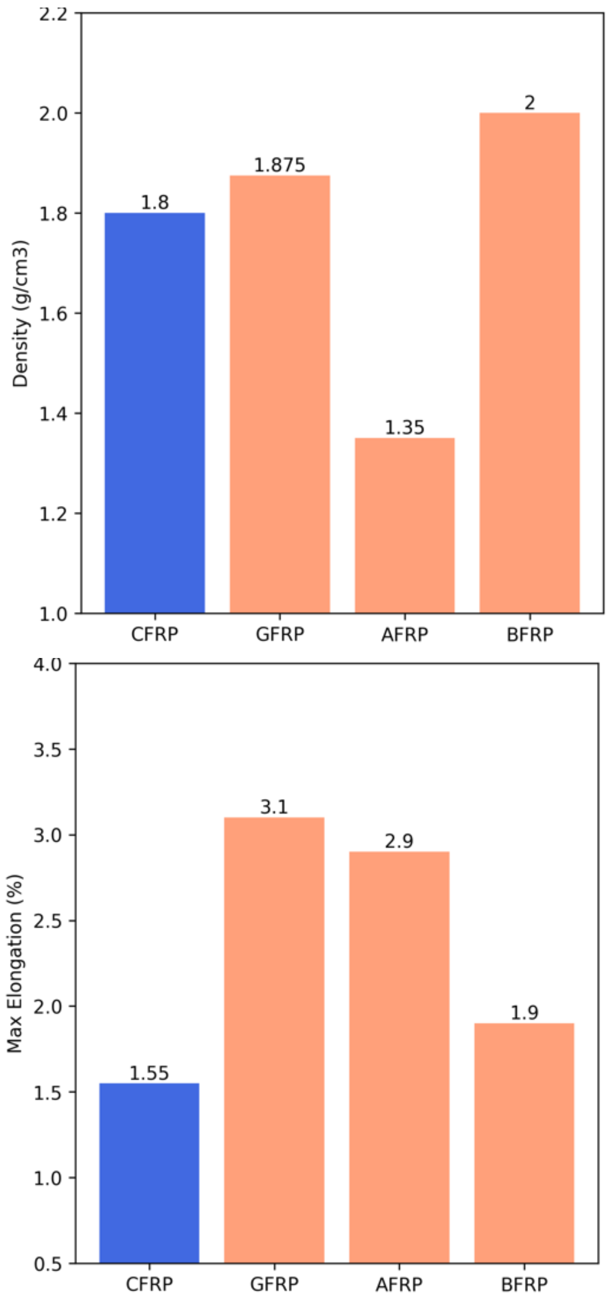
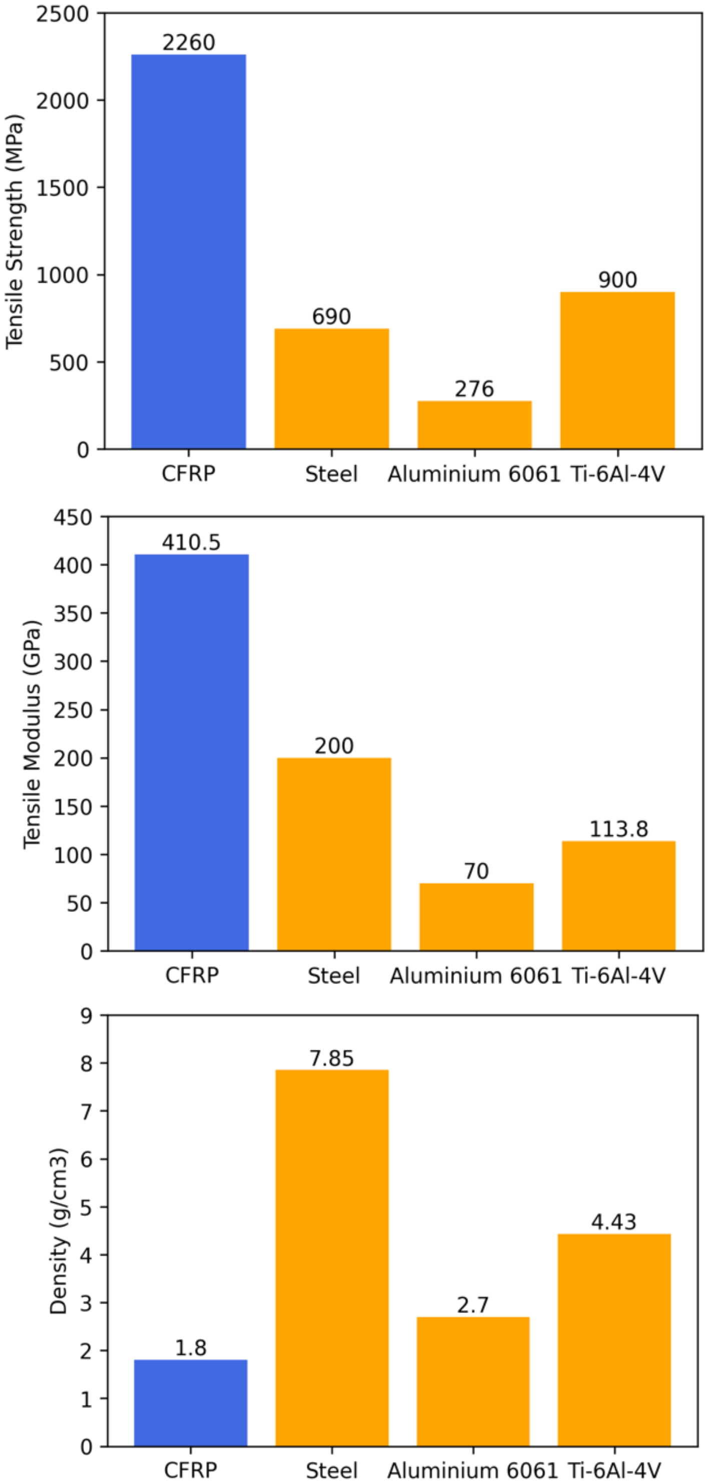


Fig. 21. Composite material technical properties

Once in the matrix, CFRP versus CF sees tensile strength reduced from 4300 MPa (CF) to 2300 MPa (CFRP) in agreement with the general mixture rules on mechanical properties.
Comparison between GFRP and CFRP shows that tensile strength is very similar but elastic modulus of CFRP is around 5 times higher for CFRP. Density is not a factor on material selection. Price differences justify wide adoption of GFRP in applications where elastic modulus is not critical.

<u>Metallic material technical properties:</u>

CFRP is highly employed as a substitute of metallic materials for weight saving purposes, it allows reductions in weight and thinner structures because of high modulus. The next graphics illustrate differences between CFRP and competing engineering metallic materials.


Tensile Strength (MPa)
0
500
1000
1500
2000
2500
2260
690
276
900
CFRP
Steel
Aluminium 6061
Ti-6Al-4V
Tensile Modulus (GPa)
0
50
100
150
200
250
300
350
400
450
410.5
200
70
113.8
CFRP
Steel
Aluminium 6061
Ti-6Al-4V
Density (g/cm3)
0
1
2
3
4
5
6
7
8
9
1.8
7.85
2.7
4.43
CFRP
Steel
Aluminium 6061
Ti-6Al-4V

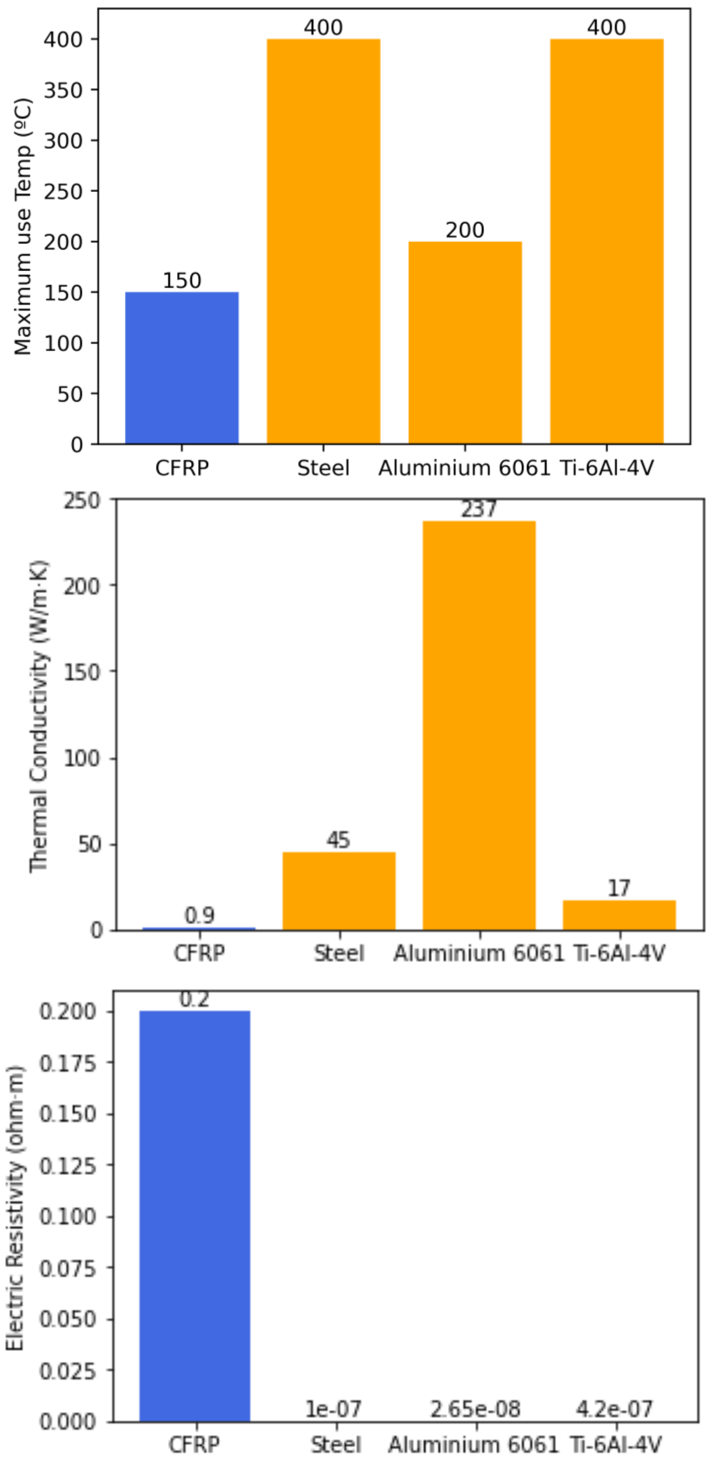


Fig. 22. CFRP and metallic materials technical properties

<u>Technical properties conclusions:</u>

Hereafter some conclusions of the study are presented:

· CF presents exceptional tensile resistance and high elastic modulus

· As CF carbon content increases, modulus does but increasing fragile failure.

· Aramid fibers and glass fibers are comparable with CF in traction resistance but CF is twice as rigid.

· Natural fibers technical performance is far from artificial fibers; advancements have been done to increase carbon content and modulus
· Among polymeric materials for matrices in CFRP, thermosets expose higher compatibility due to liquid state and higher modulus and glass transition temperatures.
· CFRP characteristics can be approximated by mixtures rules; their standalone performance is lower than CF but allows volumetric and flexural resistance.
· Among composite materials, similar performance and resistance can be achieved through GFRP with less rigidity but lower costs.
· CFRP is not only lighter than steel or aluminum, it is approximately twice as rigid than steel.
· CFRP costs are higher than steel, aluminum or glass fiber composites; this justifies niche applications for CFRPs in which performance is critical.

3.2.4. CF and composites technical properties open data

CF, CFRP and other competing materials technical data and data analysis has been compiled in open access Jupyter notebooks and CSV files.

Data and Jupyter notebooks for technical properties can be accessed through the following link:

Technical Properties Open Repositories

3.3. CFRP manufacturing

3.3.1. Introduction to CFRP manufacturing processes

CFRP entails a great effort on design for manufacturing; CFRP manufacturability, quality and cost comprehends multiple factors such as the nature of reinforcements and matrices, geometry, costs or process cycle.
Until the date, CFRP manufacturing methods have been stablished and are mature; those methods have also be classified and analyzed [11] [12] , current developments are in the field of CAM, mathematical modelling, optimization as well as in the shape freedom.
Literature has put light on process definition, and outputs, but it does not compare methods from a decision making perspective.
In this chapter, manufacturing problem complexity will be depicted identifying the different factors that affect decision making on process selection. Current processes will be analyzed in qualitative and quantitative basis.

3.3.2. Factors affecting CFRP manufacturing

Mature literature has been stablished for CFRP manufacturing, however, there is disparity between authors on the classification of manufacturing processes and the decision making process; here the different factors affecting manufacturing process are stablished holistically:

1. Plastic matrix nature: Type of polymer, thermoset or thermoplastic.
2. Type of reinforcements: Fibers can be divided between continuous and discontinuous (chopped mat, chopped fibers, bulk modelling compound) and the latter are transformed in different types of preforms; it has received the name of fiber architecture [13] [14]carbon fiber preforms can be subject to general textile shape and braiding methods.

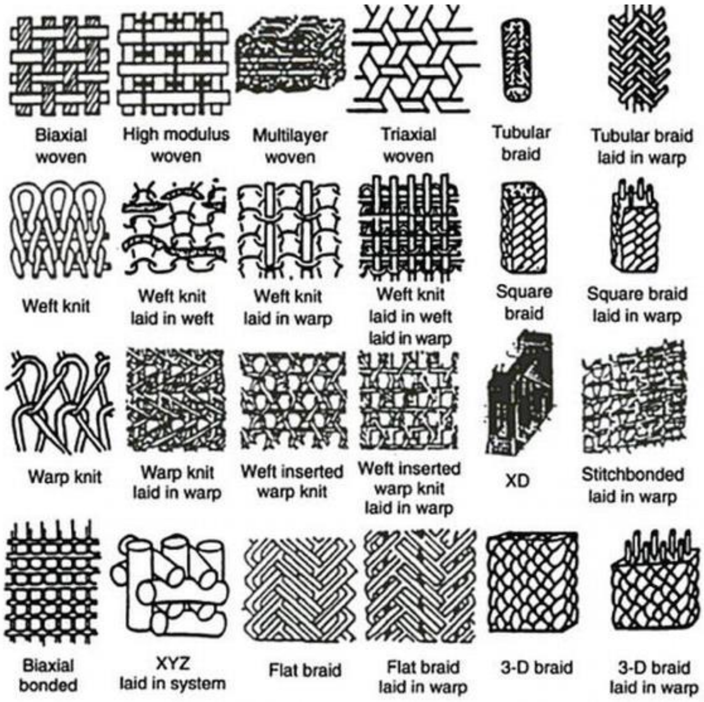


Fig. 23. List of textile structures [14]

· Rovings: Many individual filaments wound into a single strand.
· Mats: Preforms made of unidirectional filaments hold together by binders.
· Woven, stitched and braided fabrics: Multidirectional reinforcements produced by weaving, knitting , stitching or braiding continuous fibers into a fabric from twisted and plied yarns.

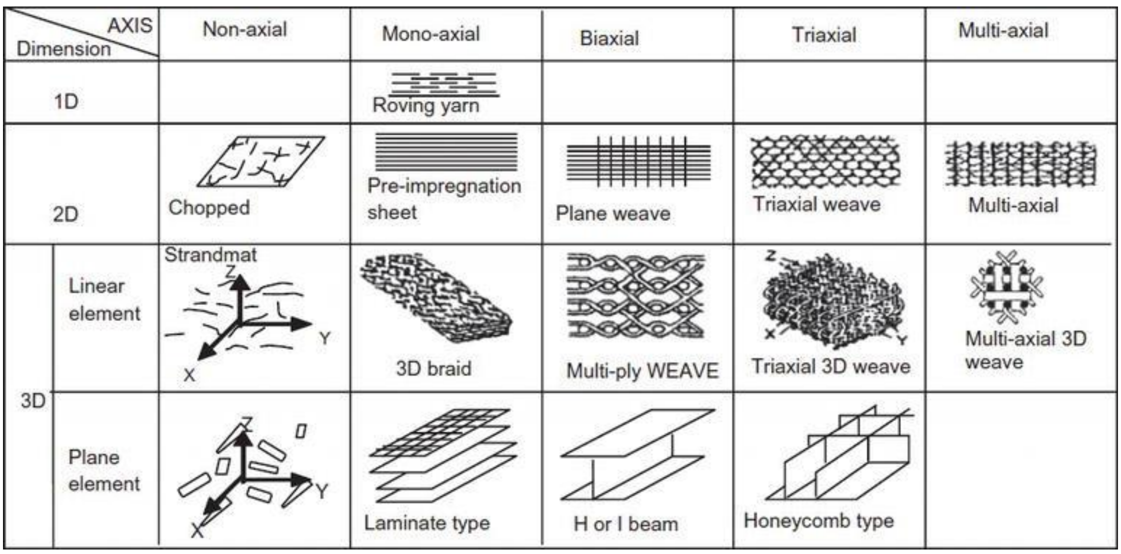
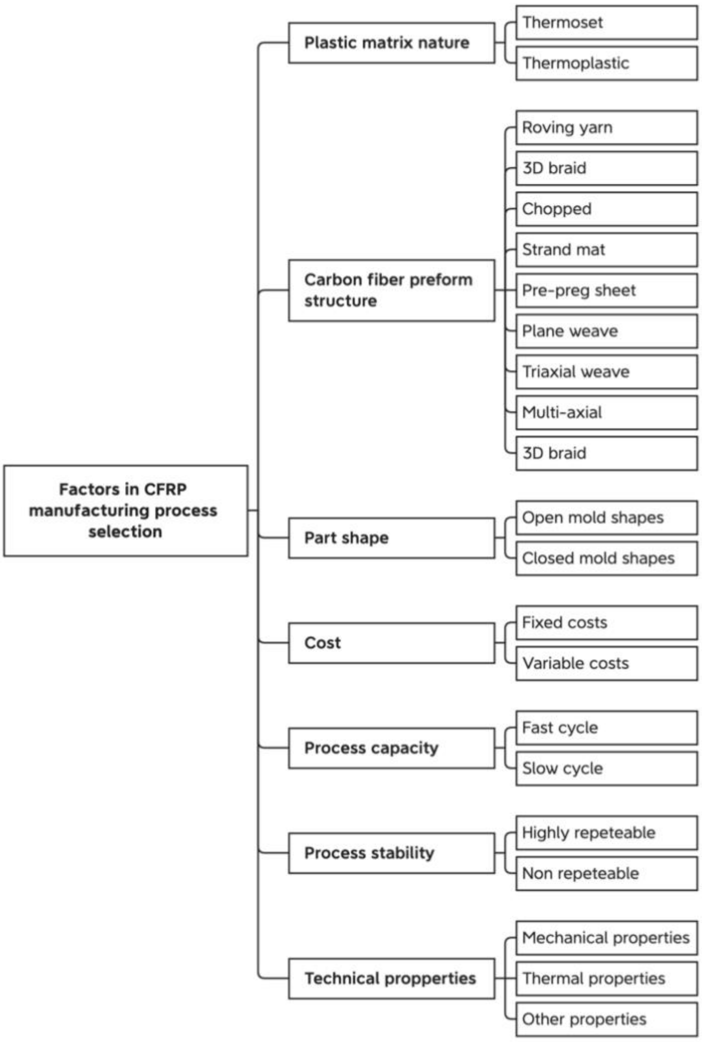


Fig. 24. Carbon fiber textile preforms [13]



3. Part shape: Part shape can be treated at different levels.
· Geometry complexity
· Need to apply multiple layers
· Geometry for demolding

4. Costs: Cost related to the manufacturing process.
· Fixed costs: Cost of machinery and fixtures
· Variable costs: Part cost including energy, raw materials and time cost

5. Process capacity: Rate of part output per time

6. Process stability: Statistical similarity between parts produced (geometry, mechanical and aspect characteristics).

7. Quality: Stability and normality of the parts produced (geometric or mechanical).

Next diagram illustrate factors involved on the CFRP manufacturing processes:

Fig. 25. Variables affecting CFRP manufacturing processes

3.3.3. Main commercial CFRP manufacturing processes.

Main commercial processes:

In the following analysis, the main commercial manufacturing processes are compared. Although many carbon fiber reinforcement composites methods have been developed, only few of them have showed the technical and economical capability to become a standard in industry.

Next, the main commercial processes will be presented in a short summary with key characteristics.

Wet lay-up: Reinforcement is placed in an open mold: Each ply is covered with catalyzed resin, and the resin is worked into the fiber with brushes and rollers to wet-out and compact the laminate. After wet lay-up, part is cured in an autoclave.

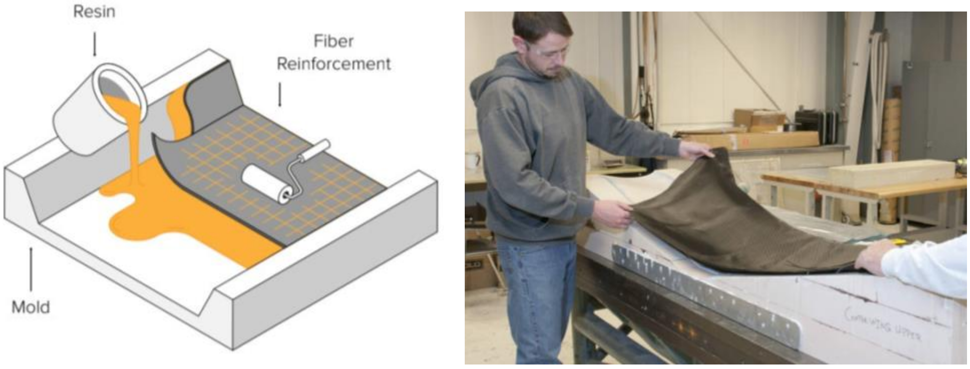


Fig. 26. Wet lay-up manufacturing process [15] [16]

Wet lay-up is characterized by the following:
· Use of thermoset resins
· Oldest and simplest method to produce CFRP.
· The part needs to be finished with other methods
· Most inexpensive and most common method to produce CFRP
· Allows high part complexity
· High process flexibility
· Quality is highly dependent on the applier's knowledge and ability
· Part output limited by the manual process

<u>Resin transfer molding (RTM):</u> Reinforcement is placed on a closed mold cavity, the mold is closed and the resin in injected into the cavity under pressure. The mold with the preform is often placed under vacuum so that the vacuum removes all the entrapped air in the preform and speeds up the RTM process. After resin transfer molding process, the part is cured usually in the same mold.

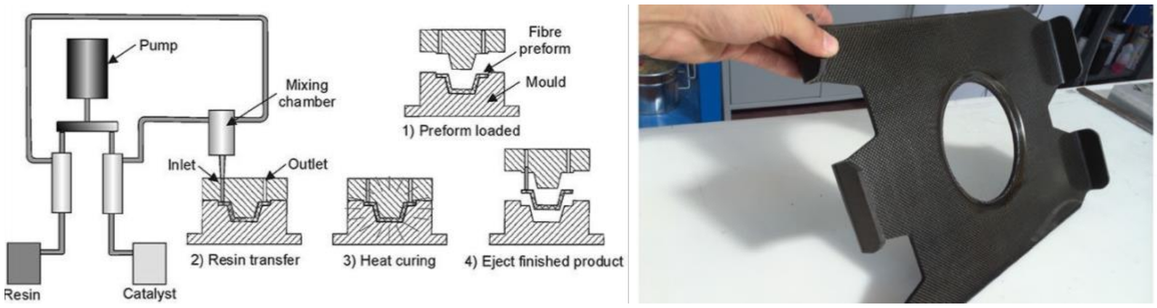


Fig. 27. RTM manufacturing process and results[17]

RTM is characterized by the following:
· Use of thermoset resins
· More expensive than wet lay up as needs pumps for resin transfer and closed mold with exact shape.
· Reinforcement is usually preformed to exactly the same shape as the mold
· Allows large parts
· Reasonable production rates
· Good surface finish
· Finished products, no need for post processing.

<u>Automated Fiber Placement (AFP):</u> Automated composites manufacturing process of heating and compacting pre-impregnated fibers on complex tooling mandrels by the use of 3 axis machines which compact cure and adhere the pre-impregnated fibers. AFP allows pre-curing although posterior phases of curing might be needed. [18]

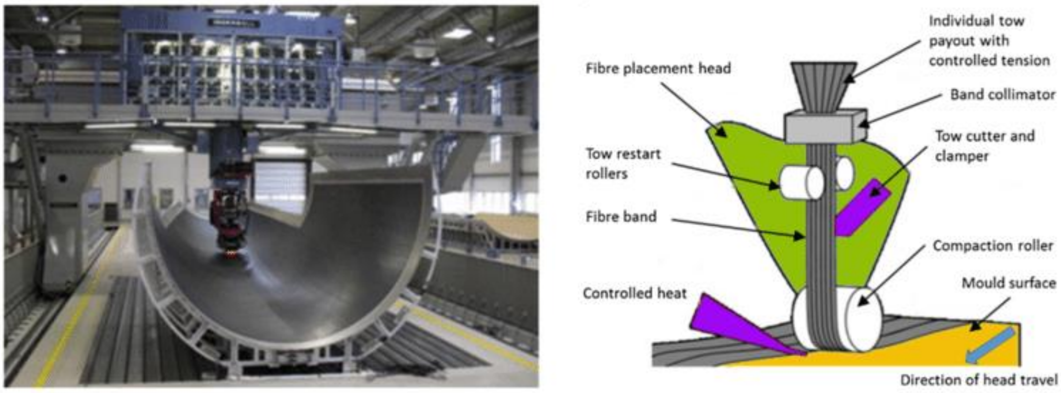


Fig. 28. AFP process and fiber placement head diagram [18]

AFP is characterized by the following:
· High process and part flexibility
· Allows production of large parts
· Allows precise control of fiber orientation
· No need to use preforms
· High process quality
· Highly automated

<u>Filament winding:</u> Winding of a continuous filament of reinforcing material covered in resin onto a rotating mandrel in layers at different angles. After winding the mandrel, the system is cured in an autoclave.

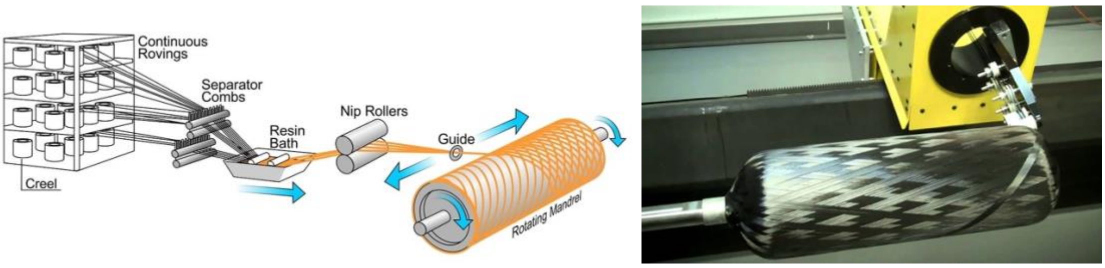


Fig. 29. Filament winding process diagram and image [19]

Filament winding is characterized by the following:
· High process and part flexibility
· Medium investments and machinery and low part costs
· High process quality
· Highly automated
· Limited to spherical and cylindrical shapes

<u>Pultrusion:</u> Is a process for producing continuous lengths of CFRP structural shapes. Pre impregnated continuous fibers are shaped under a mandrel which is heated to produce curing in a continuous basis. [20]

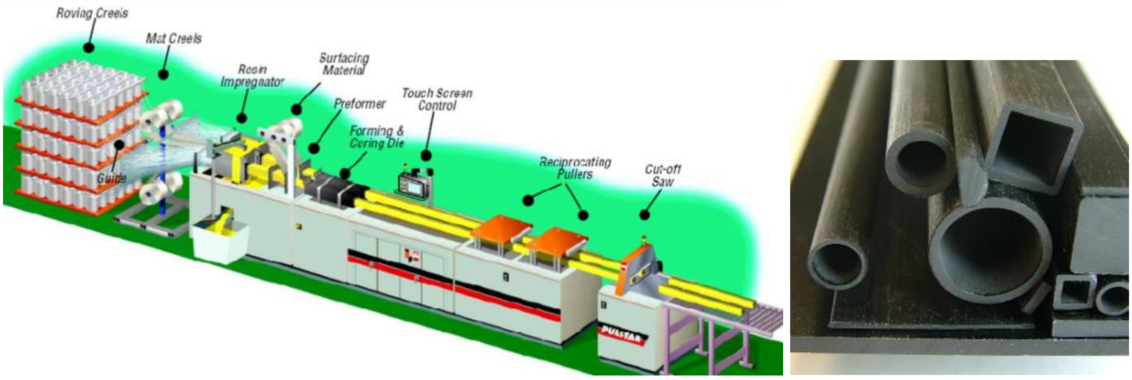


Fig. 30. CFRP pultrusion process and product [20]

Pultrusion process is characterized by the following:
· Low part cost
· High investment costs
· Parts limited to structural profile shapes.
· Limited carbon fiber orientations.

<u>Compression molding:</u> Usually employed with thermoplastic materials, in compression molding, a charge or preform (generally sheet molding compound or bulk molding compound) is placed on a closed mold, then thermoplastic material is injected by pressure.[21]

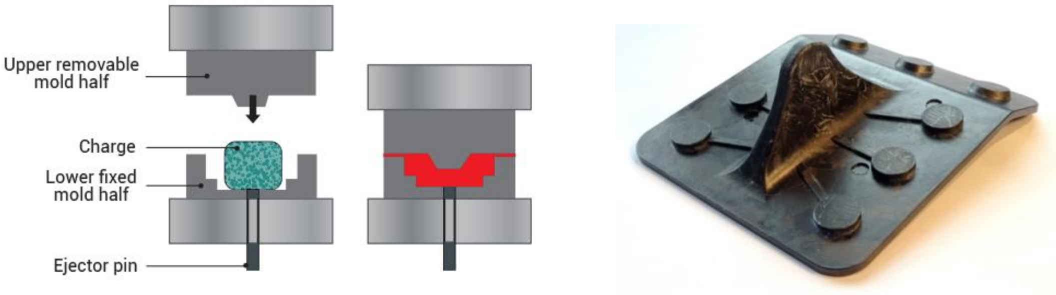


Fig. 31. CFRP Compression molding process and product [21]

Compression molding process is characterized by the following:
· Use of thermoplastic material
· Use of preforms or bulk material
· High production rates
· High quality
· Low mechanical performance

3.3.4. CFRP manufacturing processes selection

Due to high number of elements affecting CFRP manufacturing, process selection is usually based on experience and common industrial practice.

Following table summarizes the most common processes evaluating the aforementioned manufacturing factors.

	Polymer nature	Preform structure	Part shape complexity	Fixed cost	Variable cost	Process capacity	Process stability
Wet lay up	Thermoset	Pre-impregnated sheet Woven cloth	High	Low	High	Low	Low
Resin transfer molding (RTM)	Thermoset	All	Medium	Medium	Low	Medium	High
Automated fiber placement	Thermoset (prepreg)	Pre-impregnated sheet	High	High	High	Low	Low
Filament winding	Thermoset	Roving yarn	Low (only mandrell)	Medium	Medium	Medium	Medium
Pultrusion	Thermoset	Roving yarn	Profiles	High	Low	High	High
Compression molding	Thermoset Thermoplastic	All	High	Medium	Low	HIgh	Medium

Table. 1. Manufacturing processes qualitative characterization

Qualitative methods can facilitate process selection; the table below is elaborated by quantifying the relationship between factors in the manufacturing process and can help the designer in de decision process.

An interaction matrix between manufacturing factors has therefore been stablished to assess the compatibility in factor selection. The interaction matrix is shown for explanatory purposes, to access the interaction matrix the reader is referred to Annex I. Data tables.

		Matrix nature		Carbon fiber preform structure							Part shape		Cost				Capacity		Process stability		Technical properties		
		Thermoset	Thermoplastic	Roving yarn	Chopped	Strand mat	Pre-preg sheet	Plane weave	Multi-axial	3D braid	Open mold	closed mold	High fixed costs	Low fixed costs	igh variable co	ow variable cos	Fast cycle	Slow Cycle	ighly repeteabl	Non repeteable	High mech. Prop	edium mech. Pr	Low mech prop
Matrix nature	Thermoset		N.A	N.A	3	3	5	4	4	4	5	3	2	4	4	2	0	5	3	3	5	3	0
	Thermoplastic			N.A	5	3	0	4	1	1	0	5	3	0	0	5	5	0	5	0	0	5	3
Preform structures	Roving yarn				N.A	N.A	N.A	N.A	N.A	N.A	5	0	3	1	4	1	1	3	4	1	5	3	0
	Chopped					N.A	N.A	N.A	N.A	N.A	5	5	3	3	3	3	0	0	0	0	0	3	5
	Strand mat						N.A	N.A	N.A	N.A	4	5	3	3	3	3	3	3	3	3	0	3	5
	Pre-preg sheet							N.A	N.A	N.A	5	0	3	3	5	0	0	5	3	3	5	0	0
	Plane weave								N.A	N.A	3	3	3	3	4	0	3	3	3	3	3	3	0
	Multi-axial									N.A	3	3	3	3	3	3	3	3	3	3	3	3	0
	3D braid										3	3	3	3	3	3	3	3	3	3	3	3	0
Part complexity	Open mold											N.A	3	3	5	0	0	5	3	4	5	3	0
	Closed mold												3	3	3	3	5	5	5	2	5	3	3
Cost	High fixed cost													N.A	N.A	N.A	5	0	5	0	5	3	0
	Low fixed cost														N.A	N.A	0	5	0	5	0	5	3
	High variable cost															N.A	0	5	3	3	5	3	0
	Low variable cost																5	0	3	3	3	5	0
Capacity	Fast cycle																	N.A	3	3	3	5	0
	Slow cycle																		3	3	5	3	0
Stability	Highly repeteable																			N.A	5	3	0
	Non repeteable																				0	5	3
Mech. Prop.	High mech																					N.A	N.A
	Medium mech																						N.A
	Low mech																						

Table. 2. Interaction matrix of variables in the manufacturing process

This table allows the user to find relations between factors in manufacturing, the relations are quantified from 0 (non-related) to 5 (highly-related).

For a given design, the used can assign weights for the factors importance from 0 to 5, then, he can select a diversion of factors and quantify the suitability of the factors based on the obtained number.

To exemplify the selection process; the factors selection for an automotive doorframe made of CFRP will be done; as part performance is not critical, focus will be hold on reducing part cost.

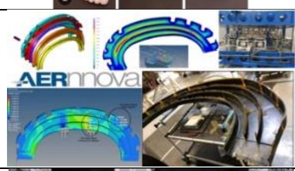
<u>For low variable cost:</u>
· Low variable cost column is inspected and decisions are taken
· Matrix nature = Thermoplastic
· Preform structure = Strand mat is the best solution
· Part complexity = closed mold is best option
· Fixed cost = not related with low variable cost
· Capacity = Fast cycle
· Stability = not related with low variable cost
· Technical properties = Medium mechanical properties are expected.

<u>If multiple factors are imposed or similar ratings are found:</u> An iterative approach must be followed.

Process selection is then complex and shortest-path or highest-constraint methods are more suitable; other methods such as experience based decision should be employed.

3.3.5. Common CFRP process applications:

Next table will compile common applications of the main CFRP manufacturing methods:

Wet lay up	· Recreational (luxury) · Sports · Highly personalized items (prosthetics) · Structural in construction (reinforcements and restoration)	
RTM	· Structural aerospace application (airframe) · Aerodynamic surfaces in aerospace (wings, jet engine) · Automotive applications (structural) · Space applications · Structural in construction	
Automated fiber placement	· Aerodynamic surfaces in wind turbine blades · Aerodynamic surfaces in aerospace · Hydrodynamic surfaces in boats · Big structural parts	
Fil. Winding.	· Fuel tanks (Hydrogen and other high pressure)	

Pultrusion	· Structural in construction · Parts for larger assemblies (structural, recreational)	
Compression molding	· Automotive application (low weight parts)	

Table. 3. Common CFRP process applications and images

3.3.6. CFRP manufacturing process conclusions:

Conclusions:

· CFRP manufacturing methods are mature and there are extensive studies on a diversity of processes part and cases.

· CFRP manufacturing processes are affected by a large number of variables; decision making process if often based on experience or highest-constraint paths.

· Variety of methods allow CFRP to be adapted to a wide range of industries and products, being the primary barriers the part cost and the low process outputs (except for thermoplastic methods).

Recent developments and trends:

· Hand-lay-up had been used to create structural parts in the past, but recent developments and specialization on the production of woven preforms have made resin transfer molding more accessible, outperforming hand-lay-up specially for structural applications.

· Hand-lay-up is currently employed by non-structural applications, for low series and highly personalized items

· Automated fiber placement is currently on development, it can produce large parts with high quality and flexibility. The process relies on CAM software which needs to take into account tension on the fibers, orientation, curvature, heating and furthermore.

· Filament winding has become a key enabling technology for the hydrogen vehicle; high pressure and risks of hydrogen storage need high strength, energy in mobility is directly affected by weight.

3.4. CFRP design methodology

3.4.1. Introduction to CFRP design methodology

In this chapter, the mechanical modelling and design methodology for CFRP materials will be treated. Besides high costs or complex manufacturing of the fibers and compounds; structural design or mechanical design also imposes a challenge for engineers desiring to take on CFRP part design and manufacturing.

The challenge of carbon fiber structural design comes determined by two main factors: First factor is the anisotropic character of the fibers; in order to maximize mechanical tensile performance, fibers need to be employed as a continuous strand versus other preform shapes or textile forms. The second factor is the layer constitution of the composites, made of multiple plies which allow for multiple combinations of non-isotropic layers.

These two factors entail some problems, first is to determine the composite mechanical characteristics, the second is to optimize the composite in order to minimize other factors such as weight. Above these two factors which constitute the basic mechanical problem definition, current challenges are to design for delamination, crash, fatigue or even manufacturing.

3.4.2. CFRP design methodologies

Classical Laminate Theory (CLT)

Most basic mechanical analysis has been depicted on the Classical Laminate Theory (CLT), the CLT is a commonly used predictive tool, which evolved in the 1960s, which makes it possible to analyze complex coupling effects that may occur in composite laminates [22]. It is able to predict strains, displacements and curvatures that develop in a laminate as it is mechanically and thermally loaded. The method is similar to isotropic plate theory, with the main difference appearing in the lamina stress-strain relationships. As with any analytical technique, some assumptions must be made in order to make the problem solvable:

Assumptions [23] [24]:

1. The laminate consists of perfectly bonded layers. There is no slip between the adjacent layers. In other words, it is equivalent to saying that the displacement components are continuous through the thickness.
2. Each lamina is considered to be a homogeneous layer such that its effective properties are known.
3. Each lamina is in a state of plane stress.
4. The individual lamina can be isotropic, orthotropic or transversely isotropic.
5. The laminate deforms according to the Kirchhoff - Love assumptions for bending and stretching of thin plates (as assumed in classical plate theory). The assumptions are:
    a. The normals to the mid-plane remain straight and normal to the midplane even after deformation.
    b. The normals to the mid-plane do not change their lengths.

Process for analysis [25] :

1. Define elasticity of each material
2. Define mechanical loads (Normal forces and moments)
3. Calculate reduced stiffness matrix for each material
4. Calculate the transformed stiffness matrix for each ply based on the reduced stiffness matrix and the fiber angle.
5. Calculate A,B,D matrices (a connection between applied loads and the strains in the laminate) depending on positions respect to midplane; by multiplying reducing stiffness matrix respect the vertical position with midplane. Assemble ABD
6. Calculate the inverse matrix of ABD, obtain abd matrix
7. Introduce mechanical loads and obtain strains and curvatures induced in the laminate by vectorial product of abd matrix by loads matrix.
8. For each ply, obtain strains and curvatures by multiplying corresponding strains by position and curvature
9. For each ply, obtain stresses by multiplying the reduced stiffness matrix by ply strains

Following chart shows CLT method for mechanical analysis:

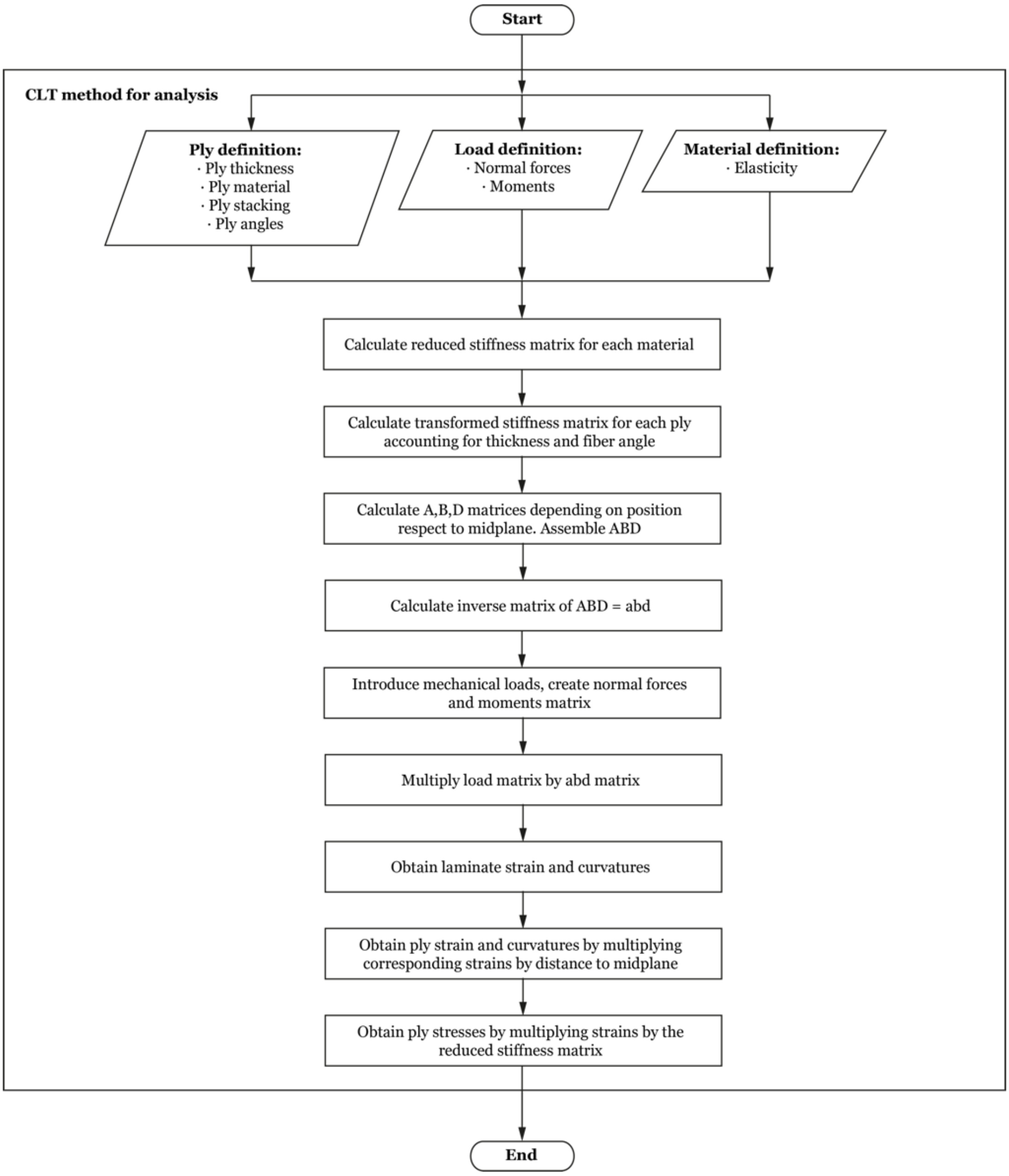


Fig. 32. Flowchart of CLT method

<u>Laminate optimization approaches</u>

Classical Laminate Theory, enabled the basis not only for laminate analysis but for laminate designs. Most basic forms of composite laminate optimization are based on iterative evaluation of the composite stiffness matrix.

<u>Process for design optimization:</u>

1. Define elasticity of each material
2. Define mechanical loads (Normal forces and moments)
3. Define possible ply combinations
4. Define objective (minimum weight, minimum deflection)
5. Iteratively calculate stiffness matrix for each combination
6. Select best laminates

The optimization of the composite layering has been subject to extensive research [26] as it comprehends optimization of discrete variables in the fields of mechanical engineering, structural or computation.

· The method of moving asymptotes a new method for structural optimization [27] (1987)
· Designing laminated composites using random search techniques [28] (1991)
· Design of laminate composite layups using genetic algorithms [29] (1995)
· A technique for the multiobjective optimization of laminated composite structures using genetic algorithms and finite element analysis [30] (2003)
· Multi-objective stacking sequence optimization of laminated cylindrical panels using a genetic algorithm and neural network [31] (2007)
· Strength design of composite beam using gradient and particle swarm optimization [32]

State of art software

As FEM (Finite Element Method) appeared and laminate calculation techniques evolved, the computational methods where introduced in software developments that led to the appearance (Computer Aided Engineering) software for composite laminates. This computer programs allows to develop structures of multiple laminate parts involving complex geometry, loads, multiple design objectives and multiple failure criteria. This software is also commonly designed to allow designer to follow the most comprehensive and productive workflow in a 3D environment that allows structural and analysis visualization to the designer.

Composite laminate design software process:

Following flowchart depicts the process employed for structural design through state of the art composite laminate software; for illustrative examples, Hypersizer software workflow is shown:

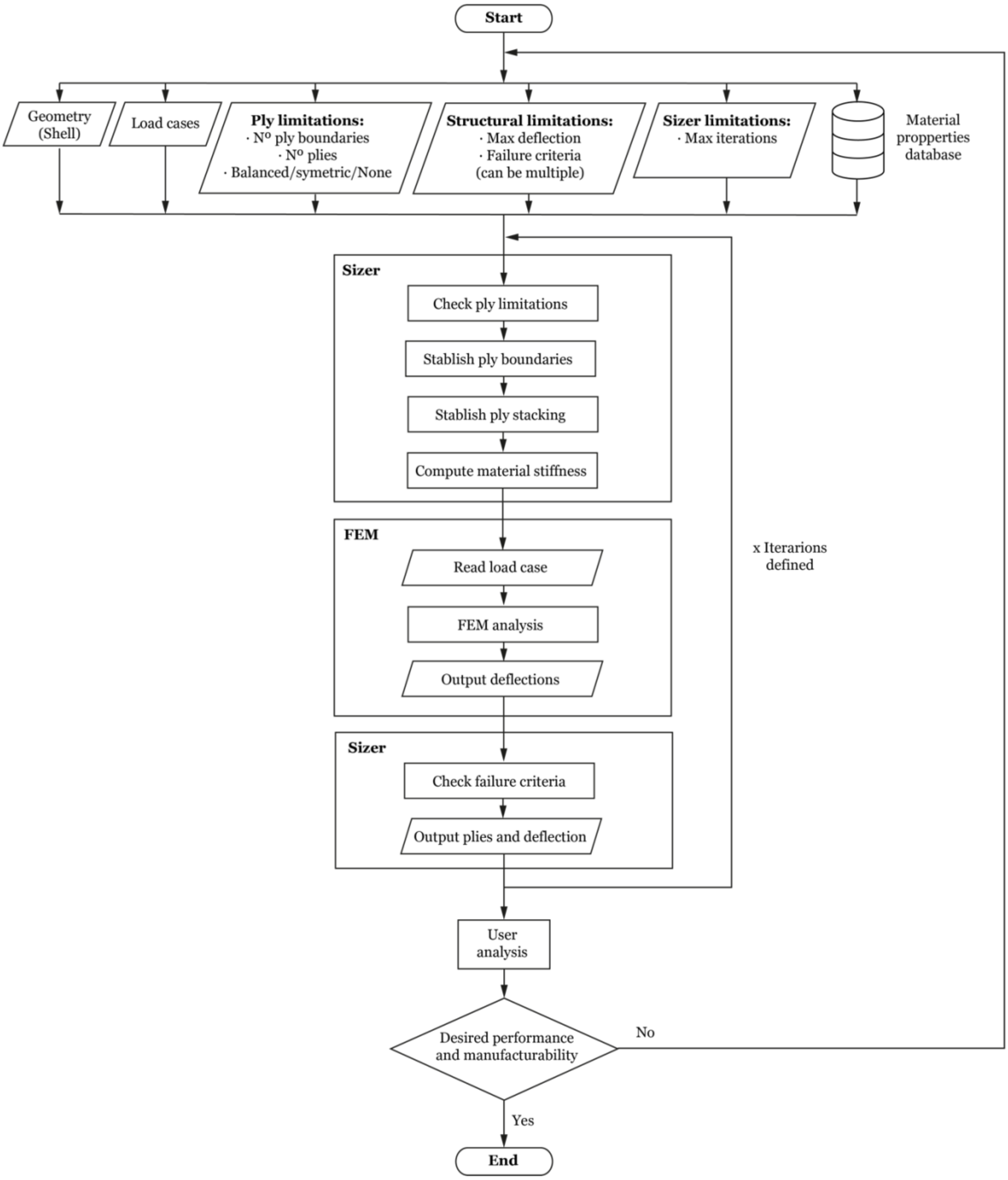


Fig. 33. Flowchart of Hypersizer software workflow

3.4.3. CFRP design methodologies conclusions

Design methodologies for CFRP systems, products and strategies show maturity, mathematical models and simulations of the laminate's behavior achieve a high degree of accuracy. Current software such as Hypersizer is commonly employed for laminate designs in the space and aerospace industries and internal processes are validated for these purposes.

This type of software is also suitable for application in automotive, sport goods, energy, gas vessels and other industrial products

Latest trends in CFRP design methodologies involve connection between CAE and CAM (Computer Aided Manufacturing) noting the big implications of failure during manufacturing, challenges are in the optimization of structures also for manufacturing.

3.5. CFRP environmental aspects

3.5.1. CFRP Life Cycle Assessment

Studies from Rhys J. Tapper, Marco L. Longana, Andrew Norton, et al have applied Life Cycle Assessment to stablish the environmental burdens of a composite material over its lifetime [33]. In this chapter, the study performed by this authors will be compiled and summarized. Conclusions will be thrown over the results obtained.

LCA process introduction:
Life Cycle Assessment (LCA) is an international standardized framework for analyzing the environmental impact associated with the life cycle phases of products, processes or activities.
LCA framework is stipulated by the International Organization of Standardization (ISO) standards (ISO 14040 2006; ISO 14044 2006).

An LCA consists of four phases of study; *Phase 1: Goal and scope definition, Phase 2: Life cycle inventory analysis, Phase 3: Impact assessment and Phase 4: Interpretation of results.*

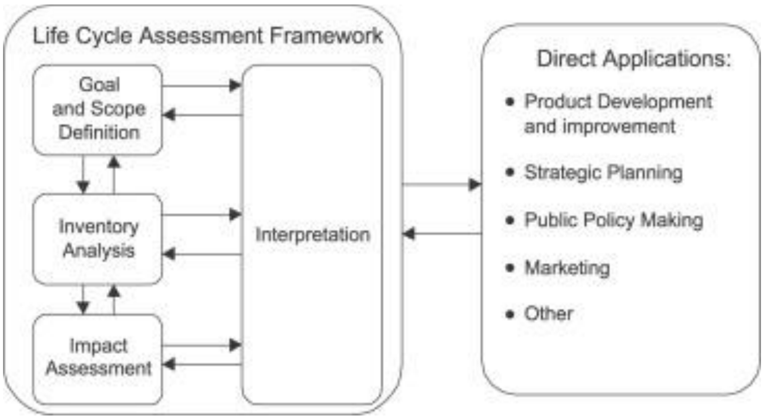


Fig. 34. Life Cycle Assessment phases and applications [34]

The *goal and scope* outline the system to be studied, describe the environmental impact categories, and identify limitations or assumptions made during the assessment. The functional unit is also selected, it can be a specific amount of material or a specific component or subsystem.

The *life cycle inventory* (LCI) identifies and sums all the relevant process flows associated with the product system. For most product-focused LCA this spans the cradle-to-grave life cycle of a product, which in turn comprises the following phases; a) raw material production, b) manufacturing, c) use and d) End Of Life (EOL).

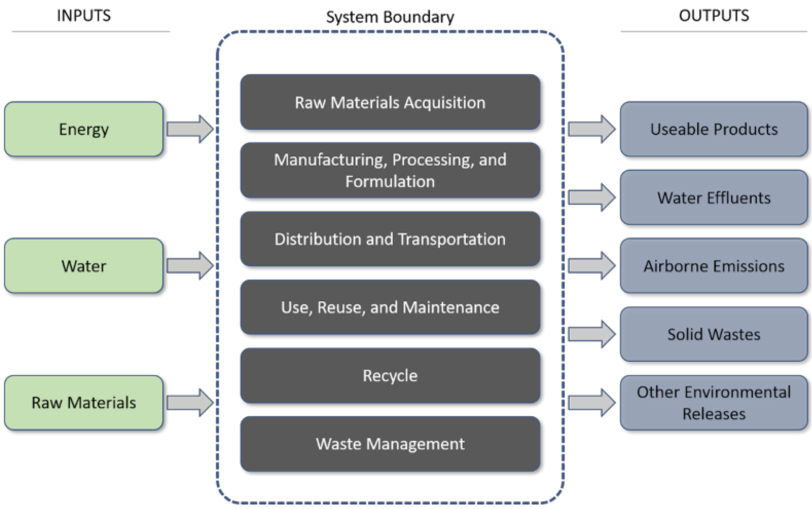


Fig. 35. Life cycle inventory definition and system boundaries [35]

The *Life Cycle Impact Assessment (LCA)* quantifies the environmental impacts of the LCI process inputs and outputs. There is a significant range of impact categories to choose from, which typically cover: Global Warming Potential (GWP), Green House Gas emissions (GHG), Fossil Fuel Depletion, Ozone Depletion, etc. GHG (unit $kgCO_2eq/kg$) is the most widely reported metric used for environmental impact across industry and academia. Relations between process inputs and outputs and the impacts produced are usually based on databases information's which are employed by software or calculators

Interpretation of Results phase draws conclusions for the assessment which are usually based on decision making on the selection of materials, products, technologies or processes. It also discusses the limitations, assumptions and decisions taken during the assessment.

Limitations:
· It is useful to create limitations in the amount of unit processes considered in the analysis (system boundary), this is a trade-off between the accuracy of the evaluation and the time required to complete. However this is a trade-of between the accuracy of the evaluation and the time required to complete it.
The necessity of setting a system boundary will undoubtedly lead to the omission of external effects that could result in a significant underestimated result. Therefore, LCA is very much a user specific evaluation.
This can make LCA comparisons on the same topic complex and regularly impractical.
As a LCA is user constructed, there are elements which require personal judgement, i.e. the system boundary breadth and the detail employed in the mapping of production phases [36]. There is also the issue of allocation, this describes the need to ensure the assignment of an impact to only one process in the system; some impacts appear in other supply chains within a shared system boundary and therefore should not be accounted for twice [37].

· For assessment of the environmental impact, individual countries rely on different energy source ratios i.e. fossil fuels, natural gas, renewables and nuclear, for electrical power. For example, a significant portion of global CF production comes from Japan which has high average GHG emissions (484 gCO_2e/kWh) associated with energy demand contribution from grid electricity. Alternatively, Sweden has lower emissions per MJ of electricity produced as its electricity production is predominantly provided by renewable sources [38].

· Resource use, i.e. energy, water, and capital, vary depending on the infrastructure, technology, and methodology used; this range is broader in more common, widely available materials as the variety of production technologies increases. Resource depletion for raw material production can also vary as a result of economies of scale between companies of small and large scale production [32]. Multinational corporations typically have processes with optimised consumptions, i.e. iron and steel suppliers, which result in substantial energy savings over smaller competitors. This can make for a complex comparison of relatively nascent CFRP production techniques with metal production established over decades of process optimisation.

CFRP Life Cycle Assessment

As the Life Cycle assessment is user dependent and functional unit dependent, as mean of examples and as mean of the potential use of CFRP, the works of Tapper et Al on the evaluation of the LCA assessment of an automotive part will be shown.

1. Goal and scope definition:

Works from Tapper et Al, LCA are based on an automotive part (panel) taking into account for the LCI the phases of Material production, par manufacturing, use, end of life and the recycling of the part. The boundaries of the system are illustrated on figure x.

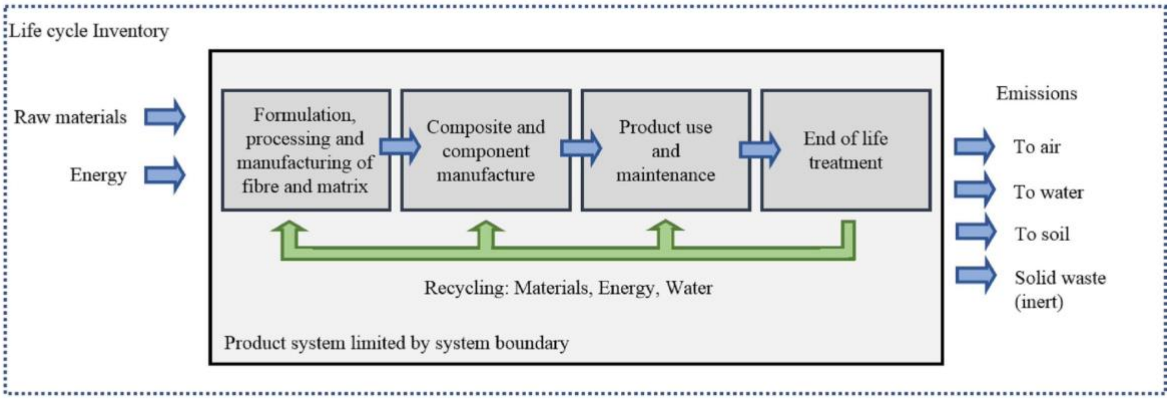


Fig. 36. Schematic of a typical LCI [33]

2. Life Cycle Inventory (LCI):

Tapper et Al evaluate different phases of the parts life and throw evaluation of multiple alternatives on part materials, part manufacturing choices, part use, and decisions on EOL. Their assessment is also focused on showing the effect on CFRP recycling on multiple cycles; the paper also comments on the LCA limitations.

Materials production:

Work performed shows high levels of GHG and Energy Use (CED) for CF production compared with other materials such as steel or aluminum. It also highlight the wide range of effects data due to differences on energy resources of countries (energy mix) and production methods (CF production is not yet as matured and optimized as steel production).

Material	CED	GHG	Cost
	MJ/kg	kg CO2eq/kg	£/kg
Steel	13-56 [10]		
	25.0–44.6 [48]	2.26-2.49 [48]	0.48-0.58 [49]
Recycled Steel	9.0–52 [10]		
Aluminium	197-298 [50]		
Fibre			
Virgin Carbon	171 [51]		
	183-286 [16,52]	–	–
	353 [53]	–	–
	478 [16,52,54]		
	198-595 [55]	–	–
	771 [56]		
	286-704 [57]	24.4–31.0 [49]	
	–	–	21.2–47.0 [58, 59]
Glass	13.0–54.3 [32,60]	–	–
	45.6 [38]	2.50 [38]	
	48.3 [45]	2.04 [45]	–
			1.59-3.54 [49,58]
Aramid	222-245 [49]	16.4–18.2 [49]	21.2 [9]
Flax	6.50-11.6 [59]	0.45 [59]	1.57-3.14 [49]
Matrix			
Thermoset			
Epoxy	140-144 [45,61]		3.00–15.0 [62]
	76-80 [16,38]		
	76-137 [57]	4.7–8.10 [57]	
Polyester	63-78 [16,63]	2.8-3.10 [16,63]	1.00–2.00 [62]
Thermoplastic			
ABS	95 [45,64]	3.10	1.22
PVC	53-80 [65–67]	2.20 [32]	1.36 [32]
Polypropylene	22.4–112 [16,45, 61]	1.85-2.60 [16,45, 61]	1.23 [49,64]
Nylon	139-145 [61,68]	6.50-8.33 [61,68]	1.66-2.55 [49,64]
PC	80-112 [32,69]	6.00–7.50 [32,69]	1.82 [49,64]
LDPE	65-92 [32,70]	1.80 [67]	1.22 [66]

Table. 4. Manufacturing energy CO_2 equivalent for different materials[33]

Manufacture:

For part manufacture multiple processes are possible with similar CED, highest affectation on LCA come from the difficulties to evaluate part complexity effects on production method as well as the effect of the production volumes. For steel comparison, for low volumes, CFRPs have showed environmental advantages over steel manufacturing on storage tanks.

Table summarising CED and production volumes of CFRP manufacturing processes. For production volumes Low < 5k ppa, Medium = 5k – 15k ppa and High = 15k – 100k.

Process	Process CED[a]	Production volume[1]
	MJ/kg	Parts per annum
Autoclave	21.9 [32]	Low
Spray up	14.9 [16]	
RTM (CF)	12.8 [16]	Medium
RTM (GF)	11.6 [71]	Medium
LRI/VARI	10.2 [16]	Medium
Cold press	11.8 [16]	High
Preform matched die	10.1 [16]	
SMC	3.5-3.8 [16]	High
Thermoplastic moulding	–	High
ATL	–	
filament winding	2.70 [16]	Medium
Pultrusion	3.10 [16]	High
Injection moulding	19–29.9 [32]	High
Prepreg (CF UD)	40 [16]	Low
Comp. mould.	7.2–15.9 [14]	

[a] Process CED is equivalent to onsite energy,[†] Costs are approximated ranges, real values are highly material specific. RTM = Resin transfer moulding. LRI = liquid reactive injection. VARI = vacuum assisted reactive injection. ATP = Automated tape laying. Comp. mould. = Compression moulding.

Table. 5. Energy and CO2 equivalent for different CFRP manufacturing processes [33]

Use:

For CFRP products, the highest environmental impact differences compared with other materials such as steel or aluminum come from the use phase.

As CFRP products are employed on highly technical and high value products such as automobile parts, wind turbines, plane structures and so on, use comprises years of functioning and therefore comprises the highest affectation on environmental impact.

For automotive products, fuel demands are a function of weight savings. Tapper et Al studies determine that for vehicles, this phase contributes anywhere between 60% and 84% of the total life cycle energy consumed. A 6-8% increase in fuel economy can be realized with every 10% weight production. Therefore, light-weighting benefits are grater realized in the transport sector.

Durability of a material is consequently associated with life-cycle impact, shorter use-phases will translate on higher maintenance/replacement costs, however CFRP have shown potential to resist same vehicle lifetimes than steel.

Taking steel as baseline, a 50% substitution of steel to CFRP resulted in a 250.000km distance. It must be highlighted that results are highly dependent on a number of factors.

Recent literature shows a breakeven
point for the virgin CFRP (vCFRP) automotive versus steel between 132.000-250.000km.

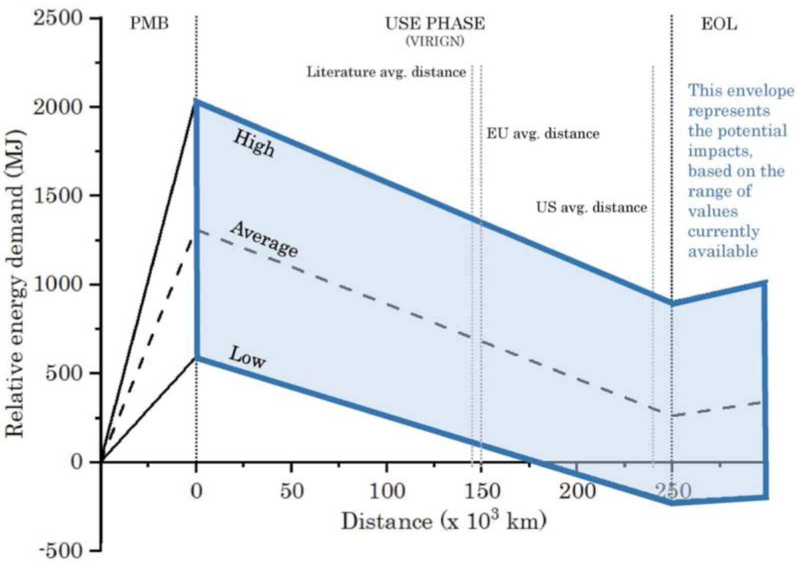


Fig. 37. Breakeven plot on distance and relative energy demand showing range of values in the literature. [33]

<u>End of life (EOL):</u>

For steel and aluminum, the melt reprocessing of EOL scrap is commonly around 95%. For CFRP, the predominant treatments at EOL are landfill and incineration. More recently recycling processes are being employed, such as mechanical methods(grinding), thermal methods (pyrolysis, micro-wave pyrolysis, fluidized bed) and chemical processes (solvolysis, acid digestion and super-critical fluid solvolysis). These processes have the potential to avoid the high energies and environmental effects for CF material production.

Process	Process CED	GHG
	MJ/kg	kg CO2eq/kg
Landfilling	0.11-0.4 [93,94]	0.09-4.61 [34,43]
Incineration	32-34[a] [43,53]	2.17-3.05 [94]
Incineration (energy recovery)	(−)31.7 to (−)34[b] [93]	2.01–3.4 [93,94]
Mechanical grinding	0.14–51 [95,96]	−36 [97]
FB Pyrolysis	7.7–30 [65]	5.4–11 [43,97]
Microwave Pyrolysis	–	–
Pyrolysis	2.8–30 [43,93]	–
High voltage fragmentation	4 [90]	–
Solvolysis	15-64 [98,99]	–
Steel recycling	11.7–19.2 [93]	0.5-1.2 [93]
Aluminium	2.4–5.0 [93]	0.3-0.6 [93]

[a] Based on CFRP epoxy component bond energies.

[b] Lit value based on CFRP epoxy calorific content with unknown recovery efficiency. FB = Fluidised bed.

Table. 6. Energy intensity and environmental impact for CFRP recycling technologies

<u>EOL recycling allocation:</u>

Reuse of material results in a reduction in the amount of production energy required on new product cycles, there are multiples approaches for LCA assessment such as *Cut-Off, Closed-loop and Substitution* with subtle differences. For closed loop-product systems, where there are no changes in the inherent properties of the recycled material, such as steel and aluminum; however LCA analysis

on closed-loop CFRP recycling is on its infancy as material performance is affected on the recycling phases.
For CFRP use, breakeven plots show, for transport products, the breakeven point stands for the distance in use needed for one material to exceed another on to reduce its environmental impact.
For CFRP, in a second use phase, breakeven point is achieved at less than 150.000km.

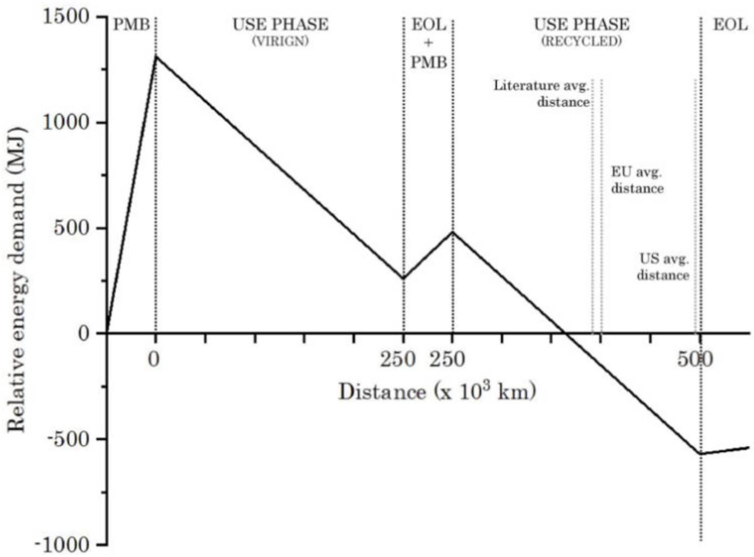


Fig. 38. Breakeven plot on distance and relative energy demand including 2 lifecycles and recycled CFRP [33]

3.5.2. CFRP End Of Life (EOL)

An ideal method for CF recycling must be ideally efficient, ecological, low cost, with lowest impact on fibers length and maintaining interfacial compatibility with new resins [39] .

CF waste types:

[40] There are three main kinds of carbon fiber residues which include:
i) Carbon fiber cutouts generated during carbon fiber production (dry fibers) with similar mechanics characteristics to the virgin carbon fibers.
ii) Pre-preg residues and semifinished products
iii) Fibers and matrices in CFRP products

Specific concerns on CFRP waste management:

Compared to other materials, CFRP present special difficulties and concerns from an environmental point of views, main concerns can be resumed as:

· **Intensive energy use for CF manufacturing:** Carbon fiber manufacturing is an energy intensive process (183-286 MJ/kg of carbon fibre) [39] that transforms the precursors with poorly ordered structure into a nearly perfect graphite structure in carbon fibre.

· **Associated emissions to the CF manufacturing process:** CF manufacturing generates environmental and human health impacts due to emissions from the oxidation and carbonization furnaces, such as HCN, NH3, NOx… [40]

· **Heterogeneity and thermoset matrix:** Composites recycling is a difficult process dure to the heterogeneous nature of the matrix and the reinforcement, especially in the case of thermoset composite. [41]

CF recycling has mainly consisted on the recuperation of fibers from the polymeric matrix and the remanufacturing of recycled fibers in a useful product.
However, in CFRP constituted by thermoset polymeric matrices, recycling process is more complex due to the heterogenic nature and difficulties to release the fibers.
Then recycling process changes if the matrix is thermoplastic or thermoset.
For thermoplastic matrices, it is possible to melt down the composite to change its shape and remodeling it to manufacture new products [8].
For CFRP constituted with thermoset matrices as phenolic resins or epoxy, these cannot be reprocessed, recycled and restored into their monomer shape due to the crosslinked 3D structure.
New developed process designed to release embedded CF on a thermoset matrix are generally based on depolymerization of the matrix on a complex mixture of gas, liquids and solid chemicals

· **Importance on fiber continuity and length:** High added value CF applications are based on the exceptional mechanical properties of the fibers, which need to be continuous on the part, CF is then, adapted to part dimensions and the specific geometry of a design; current designs and business models do not take the whole CF lifecycle into account.

<u>Current CF waste management methods:</u>
Current literature exposes classification and characterization on recycling methods [42] [43] [44]:

There are three main strategies to treat CF residues;
i) Disposal (dumps)
ii) Energetic revalorization (incineration)
iii) Recycling (mechanical, chemical and thermal methods)

EU place restrictive legislation for dump disposal of CFRPs, which doesn't allow to recover energy from composite materials.

Incineration allows to recover energy from disposal products, but it releases great pollutants quantities to the environment, is not considered a sustainable solution for waste management in the long term [41]

Therefore, other methods have been developed to diminish CF waste impact on the environment and create high added value products.

Following illustration shows state of the art methods on CFRP waste management:

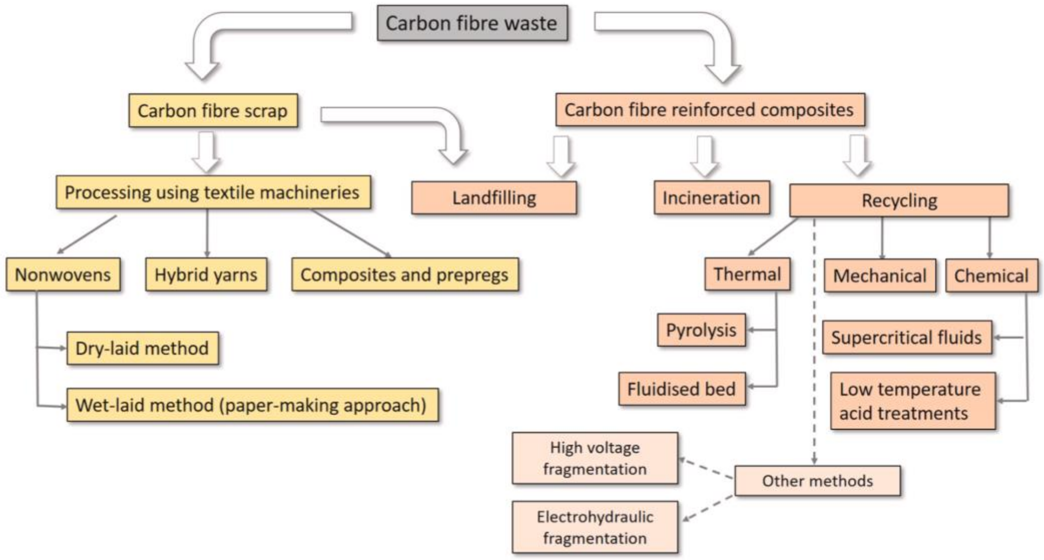


Fig. 39. CFRP waste and dry scrap management routes. [42]

Detailed description of current recycling methods can be found on the literature.

CFRP waste management methods evaluation:

Despite the aforementioned recycling methods can be promising in terms of greenhouse emission, energy use and material savings, financial viability is directly related with the energy consumption costs and the value of products obtained.
Each CFRP and CF recycling methods imply different CF ranges, superficial characteristics and environmental impact. This chapter will cover the financial viability of the method.

Phuong Anh Vo Dong et Al [45] , Tapper R, Longana M et Al [46], put great effort on the economic and environmental assessment for CFRP waste management. These authors review different environmental assessments on CFRP recycling; wide authors opinion, assumptions and environmental assessment methods difficult decision making and comparison between works.
Phuong Anh Vo Dong et Al, propose a methodological framework for the design and deployment of CFRP waste supply chain considering economic and environmental criteria. System boundaries presented are then, limited to waste value chain.

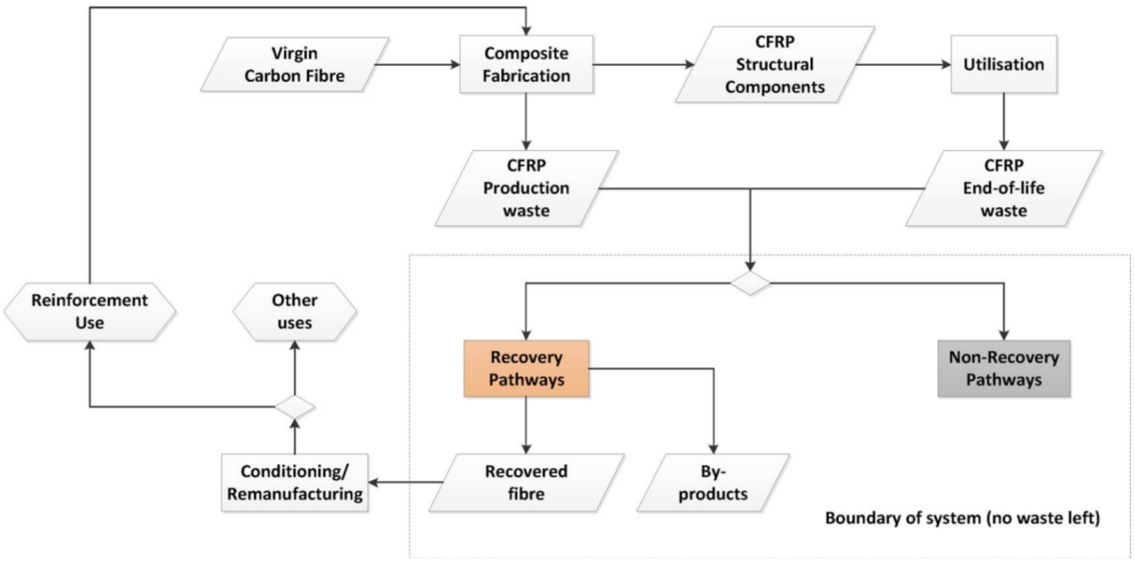


Fig. 40. Boundary of the studies system.[45]

<u>Material flows on different waste management systems:</u>

Assumption thrown by the article are based on different estimations extracted from the work on different authors for the characterization of the different methods on the non-recovery and recovery pathways.

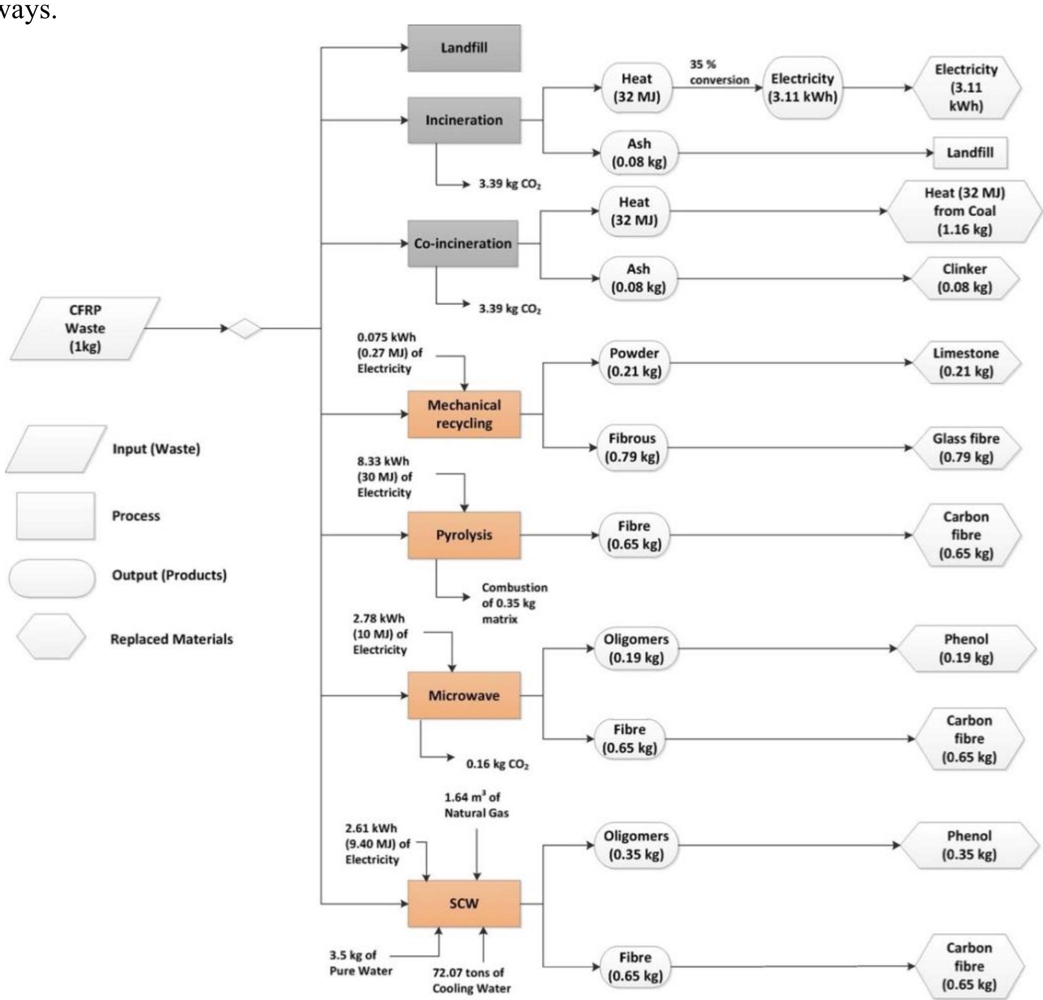


Fig. 41. Material flows on the studied system. [45]

Economic evaluation on CFRP recovering pathways:
Following chart shows the economic evaluation for non-recovering processes (Landfill, incineration, co-incineration) and recovering ones (Grinding, pyrolysis, microwave, SCW (SuperCryticalWater). Efficiency of the different recycling methods appears based on three indexes; operational cost, average cost per mass unit of recovered fiber (UCW) and the final value of the recovered CF (RCW). It must be noted that in recovery methods, the net savings proceed from the different of the process costs (UCW) and the earnings of the recovered fibers (RCW).

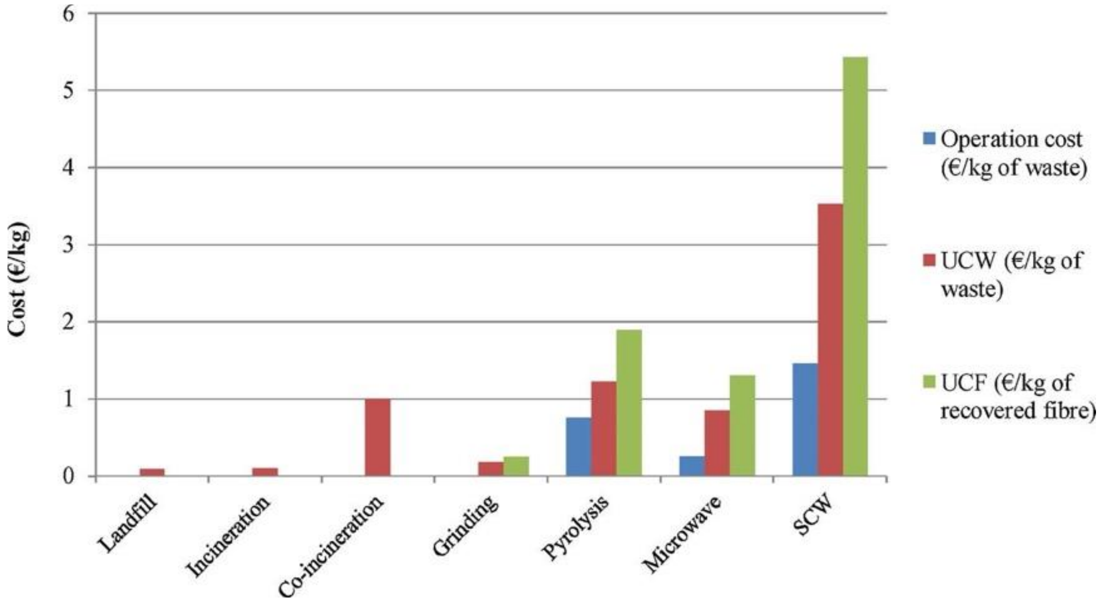


Fig. 42. Economic assessment of the studied pathways. [45]

Environmental evaluation on CFRP recovering pathways:
Three indicators for GWP (Global Warming Potential) impact are employed, GWPP (GWP impact of process), GWPA (GWP impact of substituted products) and the GWPTOT(Total GWP of the system).
Not surprisingly, recovering methods allow to reduce GWP of potential waste, justified by the high quality of the fibers produce and the subsequent energy intensive process that would be needed to remanufacture them.

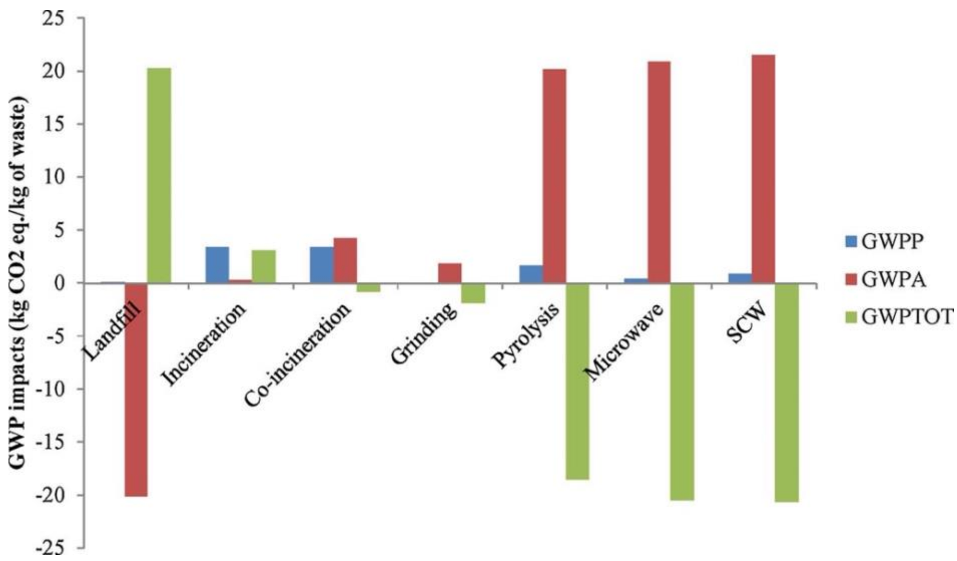


Fig. 43. Environmental assessment of the CFRP waste treatment techniques. [45]

CFRP waste management conclusions

Waste recovery methods are currently on a mature state and allow for a high level of CF recovery (mass) with exceptional mechanical properties. Recovery process selection is based on the quality of the recovered fibers, grinding methods allow to recover fibers of lower quality (components, CF length and CF structure) that can be employed as fillers on low value applications. For pyrolysis, microwave and SCW, high levels of inversion and energy are required, but allow high quality CF recovery.

For non-recovery methods, incineration methods imply the liberation of pollutants to the environment, landfilling having the lowest cost imply high GWP due to the need to produce new CF. Regulation plays than, a big driver on CRFRP waste management development, having the potential to favor the economics towards recovery processes by raising landfilling costs.

Developments of SCW methods have shown great potential for high level of CF recovery and high TRL. Companies will play a big role on recovery methods adoption which can be driven by design for life cycle, in which designs are planned having the CF recovery in mind; some challenges to overcome is the technical evaluation and quality assurance of fibers recovered and lowering the energy consumption of recovering methods.

3.5.3. Conclusions of CFRP environmental aspects

Next, conclusions of the environmental aspects of CFRP use, disposal and recycling are treated.

· **CF production is a highly energy intensive process,** this fact translates into high volumes of equivalent CO_2 which have repercussion through the entire product lifecycle.

· **CFRP employment is only effective environmentally when employed in systems in which weight is highly associated with energy consumption** (transport as an example) **or clean energy output** (wind turbines).

· **Automotive CFRP products require a high life expectancy to compete with traditional materials (aluminum or steel) in environmental terms,** highest energy savings are achieved in the use phases of the LCA.

· **CFRP EOL processes are not yet mature and critical for CO_2 savings,** as CF production imposes high volumes of energy consumption more than one life cycle is needed in order to improve steel or aluminum materials environmental performance.

· **Highest product performance is achieved through CFRP products that employ thermoset plastics difficult to recycle,** recycling methods are complex and consist on extracting the carbon fibers from the thermoset matrix.

· **CFRP recycling processes imply loss of material performance, as performance recovery grade is improved, the recycling process is more energy intensive:** highest recovery grades are linked to processes such as Supercritical Water which involve high energy consumptions, lower CF grade recovered allows for lower energy consumptions but performance levels of CF are reduced.

· **CFRP designs are highly dependent on fiber length and integrity and do not take into account material recovery,** CFRP performance is highly dependent on CF and therefore to the length of fibers.

4. CFRP market

4.1. Introduction to CFRP market

Until the date, CFRP market studies are scarce; CF market has been studied by the large CF manufacturing companies and some consulting firms. CF manufacturing companies analysis is driven by the compilation and analysis on historical sales data [47]; large consulting firms on business strategy have shown analysis on CFRP depicting key market drivers, market structure as well as forecasts [48]. Academic publications on CFRP market are also rare [49] [50], in the context of plastics market, exposing general data on market structure, historical facts and forecasts.

Current market analysis has had limited open access, and does not expose methods or data sources for analysis or forecasting.

4.2. Methodology on CFRP market analysis

For CFRP market analysis, common methods in the field of market analysis will be employed, that is; PESTLE (Political, Economic, Sociological, Technological, Legal and Environmental) analysis will be employed to assess the environmental factors affecting industry; market trends will be identified on key market drivers and blockers; current market data will be analyzed with quantitative and qualitative methods; finally, forecasts will be produced based on time series analysis.

As the study is performed, multiple insights and observations will be thrown. For all these analysis, free access data will be collected and compiled.

The following scheme shows the factors involved on the CFRP market analysis:

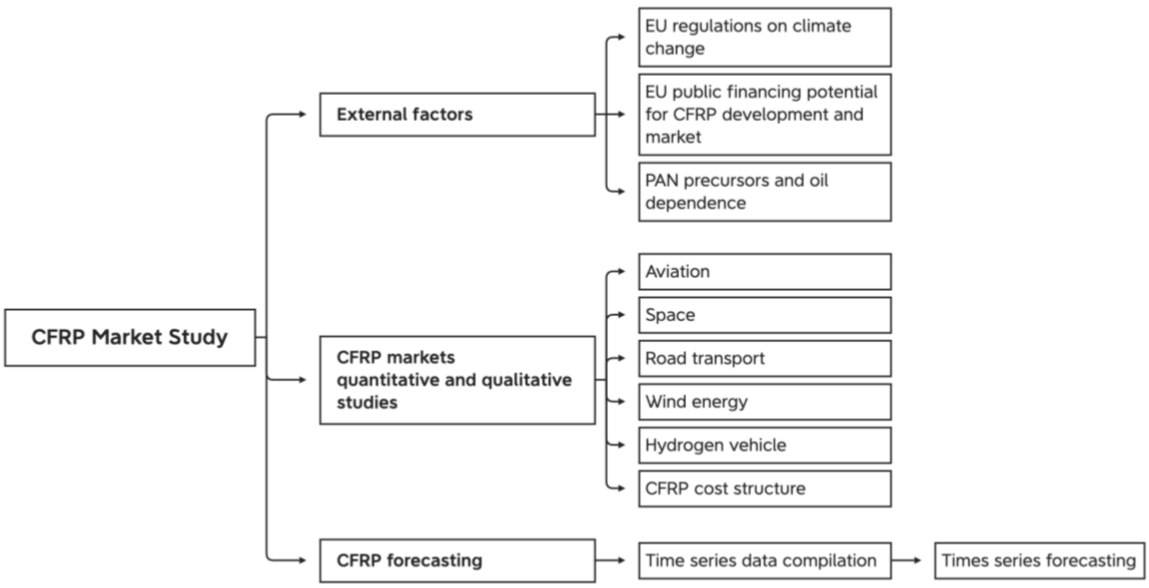


Fig. 44. CFRP market study structure

4.3. External factors.

4.3.1. European political context.

<u>Introduction:</u>

Government policies are among the main external factors affecting the market on the adoption of CFRP technology, this association comes from the exceptional strength to weight factor of these composites which allow for weight reduction and energy consumption,

Europe policies on climate change [51] date back to the creation of Kyoto Protocol (1992), year in which this international agreement stablished goals for gas emissions to control environmental safety. At that year, the international agreement recognized carbon dioxide (CO_2) as the primary driver of climate change through greenhouse mechanisms; since then, science advancements and policies have found ways to quantify the effect of different activities on climate change.
Present chapter will show Europe policies on climate change as an external factor affecting CFRP market, then it will compile historical data on agreements, reduction on CO_2 and the effect of those policies on technological development.

Europe commitments on climate change:

Following table shows a resume of the EU policies on climate change through the years. Reduction targets are stablished taking 1990 levels as reference.

Year	Commitment	Measures	Affected gas	Reduction achieved
2008-2011	Kyoto Protocol 1st commitment period	· Global reduction emission's average 5% compared to 1990 · EU-15 commitment 8% from 1990	· CO_2 · CH_4 · N_2O · HFCs · PFCs · SF_6	· Target: 8% · Achieved: 11,7%
2013-2020	Kyoto Protocol 2nd commitment period	· EU countries commitment to 20% compared with 1990. · EU responsible for emissions in sectors covered by ETS systems · Nations responsible for other emissions · Plan to achieve reduction: 2020 climate and energy package	· CO_2 · CH_4 · N_2O · HFCs · PFCs · SF_6 · NF_3	· Target: 20% · Achieved: 31% great affectation by the pandemic
2020	2020 Climate and energy package	· 20% cut in greenhouse gas emissions (from 1990 levels) · 20% of EU energy from renewables · 20% improvement in energy efficiency **Emission reduction** · Achieved through two systems: - EU emission trading system covering large facilities (industry) and aviation (40% of emissions - National emission reduction targets (Non ETS) accounting for 60% of total EU emissions → Effort sharing decision **Renewable energy:** · Binding national targets → Renewable Energy directive - 20% target for 2020 - 10% share of renewables in transport **Financing:** ·Ner300: Carbon capture and storage ·Horizon 2020: funding for research and innovation	· CO2 · CH4 · N2O · HFCs · PFCs · SF6 · NF3	· Target: 20% · Achieved: 31% great affectation by the pandemic
2030	2030 climate and energy framework	**· Created on 2014.** **Key targets for 2030:** · At least 40% cuts in greenhouse gas emissions (from 1990 levels) · At least 32% share for renewable energy ·At least 32,5% improvement in energy efficiency Greenhouse targets by: · EU emissions trading system	· CO_2 · CH_4 · N_2O · HFCs · PFCs · SF_6 · NF_3	· Target: 40%

2030	Europe Green deal	· In September 2020 proposal to increase the target of greenhouse emissions to a 55% reduction (from 1990 levels) of the 2030 climate and energy framework	· CO_2 · CH_4 · N_2O · HFCs · PFCs · SF_6 · NF_3	· Target: 55%
2050	2050 long-term strategy	· Net-zero greenhouse emissions	· CO_2 · CH_4 · N_2O · HFCs · PFCs · SF_6 · NF_3	· Target: 0% net emissions

Table. 7. Summary table of Europe commitments on climate change mitigation

These commitments have also translated on multiples policy instrument to catalyze change; this instruments will be reviewed on the next section.

Europe regulations on climate change:

In order to catalyze change on climate change reductions, Europe has employed multiple regulations which drop down at Europe and Member levels.

Following table compiles regulations employed by EU and the Member Nations to achieve emission reduction targets:

Regulation	Implementation level	Regulations
ETS (EU Emission trading systems)	European	· Large power plants · Large industrial plants · Aviation transport
Effort Sharing regulations	National	· Road transport · Buildings · Agriculture · Power plants not covered on ETS · Industrial plants not covered on ETS
LULUF (Land use and forestry regulation)	European	· Land use and forestry

Table. 8. Summary table of European regulations affecting climate change

European financing affecting CFRP development:

By direct or indirect financing, Europe policies get implemented. Developments on CFRP manufacturing are potentially financeable with the following instruments at European level.

Next, the primary financing instruments affecting CFRP development at European level are exposed:

2021-2027 Multiannual Financial Framework [52] [53]: Is the long term budget for European development. Between its very diverse instruments, the ones affecting directly or indirectly CFRP development are selected; showing the taxonomy of the budget [54].

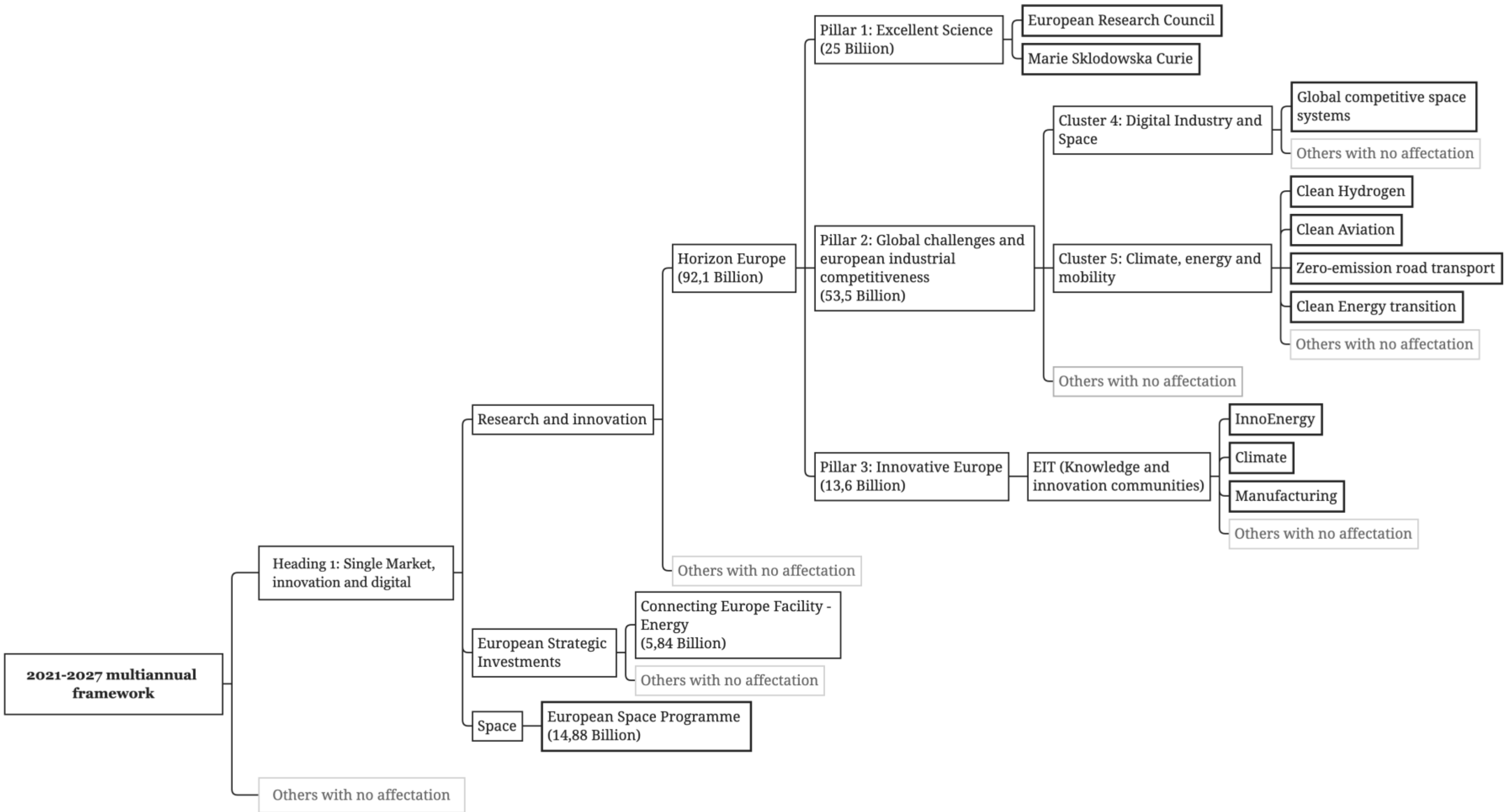


Fig. 45. 2021 multiannual framework taxonomy affecting CFRP development and market

NextGenerationEU: Is the recovery plan which originates in the COVID-19 pandemic, not aiming only to recover the economy but also to produce change in critical areas affecting the economic structure of the Union. This instrument offerst 338 Billion in grants and 385,5 Billion in loans that will be employed by the Member States to support reforms and investments with the following goals: NextGenerationEU funds, are more flexible in their implementation than the 2021-2027 multiannual work, bu also share common goals with the 2021-2027 multiannual financial framework.

Following charts, illustrate the taxonomy of EU funds affecting CFRP development directly or indirectly.

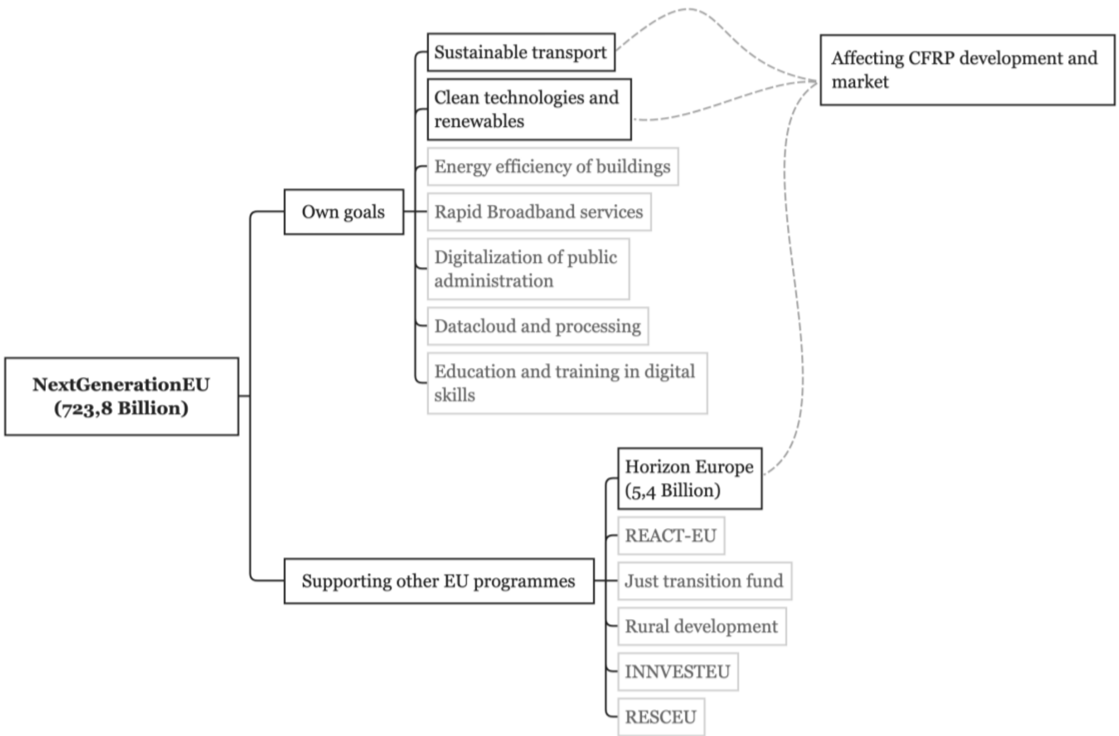


Fig. 46. NextGenerationEU funding potential for CFRP development and market[53].

<u>Conclusions on European political context:</u>

European policies on climate change are among the most deciding factors that have affected CFRP market and development as is an enabler technology for efficiency increase in mobility, energy and other applications. Conclusions of the study are highlighted next.

· **Emission reduction targets increase year by year**, European politics show tight agreement between economic development and environmental safety.

· **Multiple energy efficiency measures have been implemented through the years** in many applications (ICE motors efficiency increase, turbines, developments on wind generation) some of the technical developments **have reached a ceiling on efficiency** through technique (not material); to achieve further emission reduction material change is needed, **carbon fiber has an opportunity in this market.**

· **There is wide room for emission reduction in multiple sectors which entails wide CFRP adoption potential;** current emission levels are far from those required in 2030.

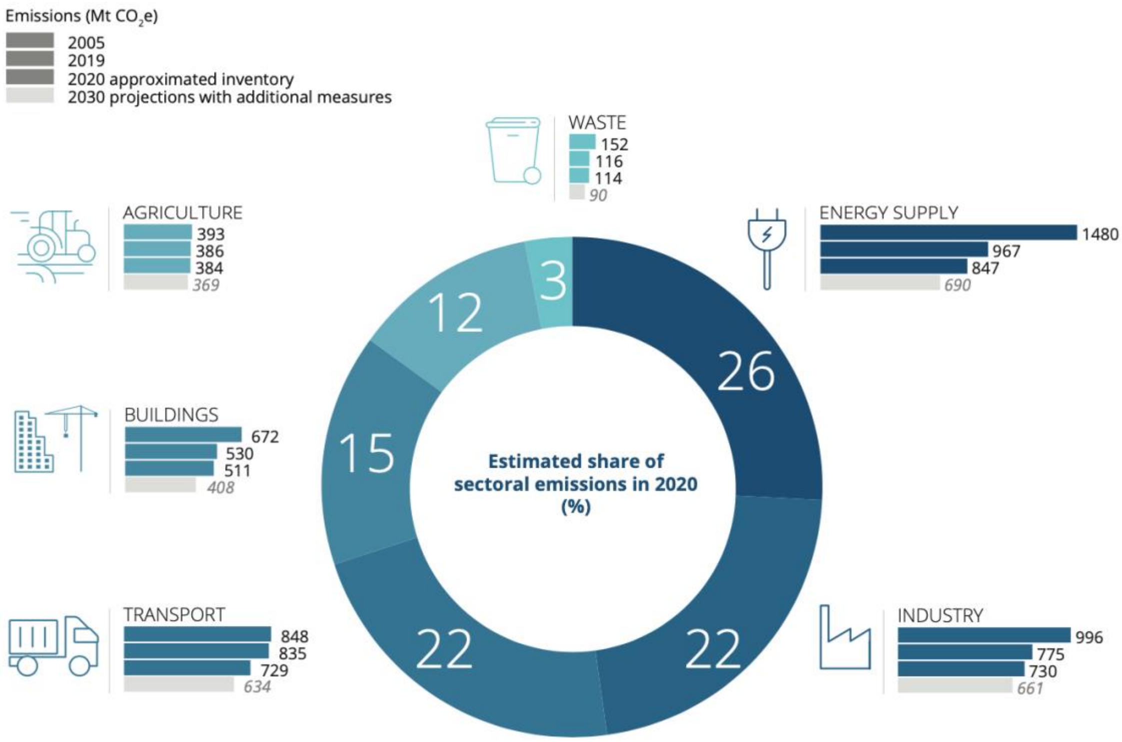


Fig. 47.Emissions Mt CO_2 eq by sector, year and targets [52]

· **Current situation on European funding is prone to benefit CFRP market on adoption and development.**

4.3.2. CF dependency on oil.

Acrylonitrile, a major component in the production of PAN fibers; is currently obtained as a petrochemical and thus, CF price is highly dependent on oil prices [55].

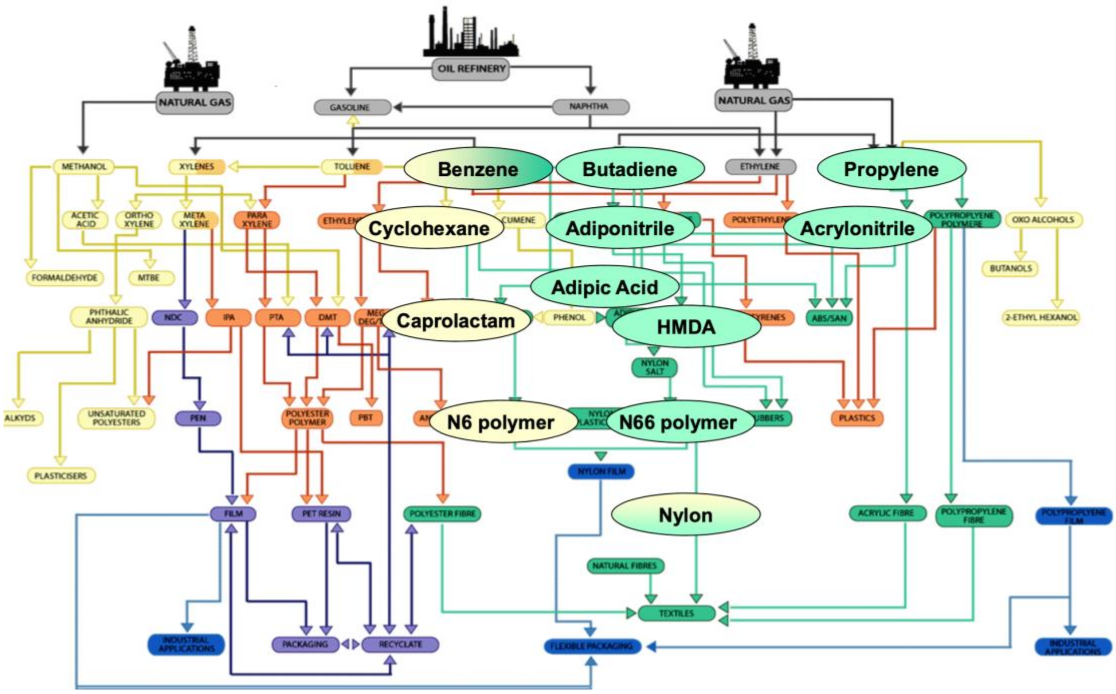


Fig. 48. Petrochemical materials and precursors.[55]

It is important to note the high complexity and volatility of oil and gas prices; in this industry, current cost stabilization and reduction strategies are put on the specialization of the chemical producers, the investment on analysis, and the import/export of products as prices change [56].

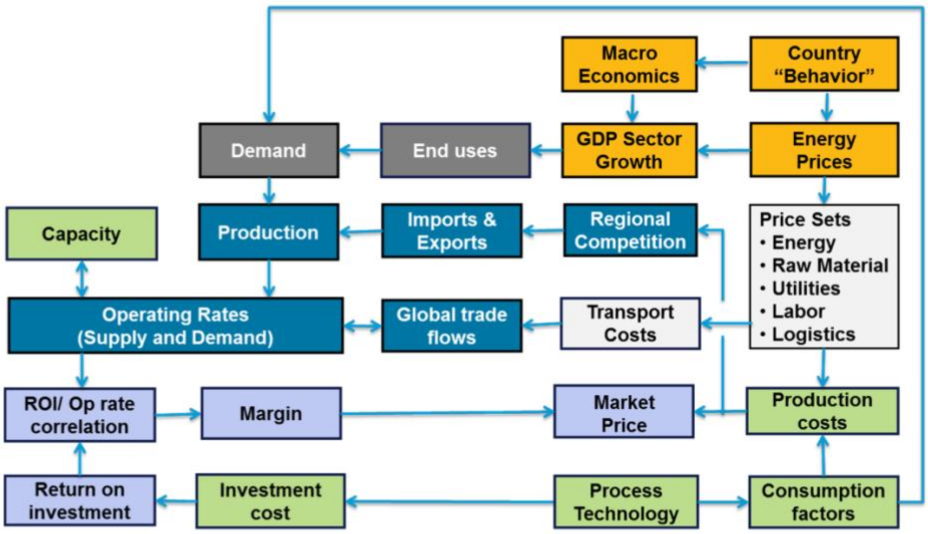


Fig. 49. Chemical industry dynamics relationships [56]

Another of the strategies employed to control petrochemical prices is conversion, in which petrochemical products (feedstock) is fractioned for the obtention of other products:

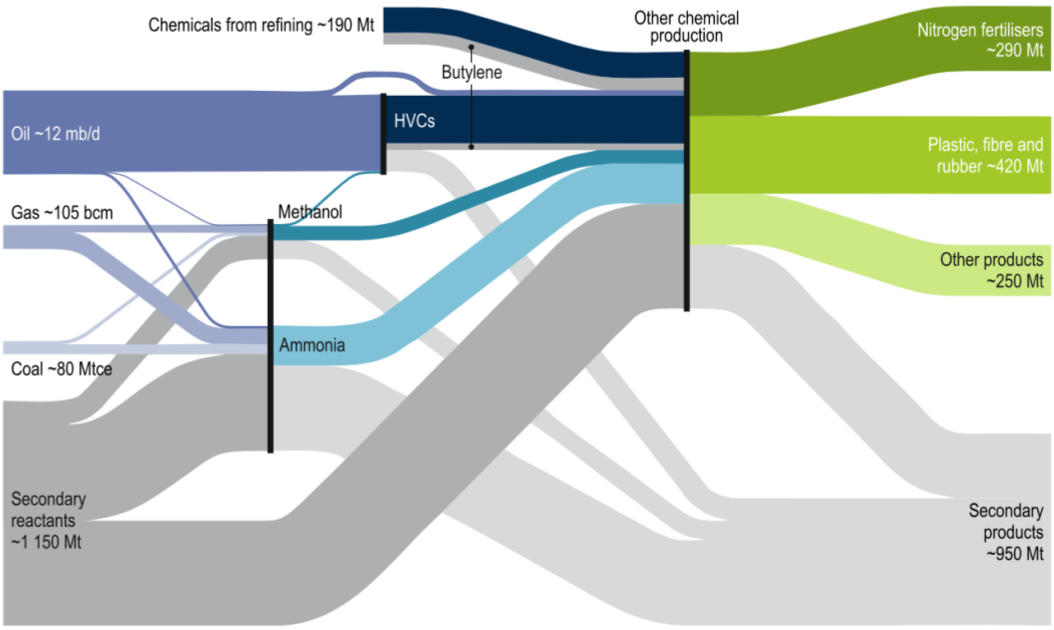


Fig. 50. Passage of fossil fuel feedstock through the chemical industry in 2017 [56]

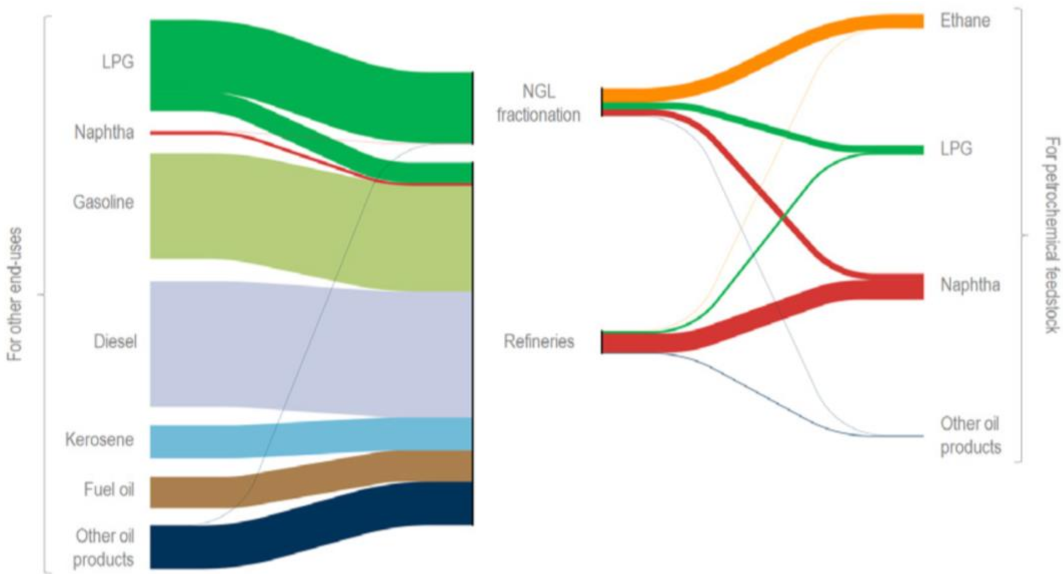


Fig. 51. Destinations of oil products from NGL (Natural Gas Liquids) fractionation and refineries.

<u>Conclusions on CF dependency on oil prices:</u>
Carbon fiber costs are affected mostly on the prices of acrylonitrile and then are subjected to fluctuations on prices dependent on oil. For the future, European decisions on fossil fuel use as energy are prone to limit feedstock employment to petrochemical products

As will be shown on the price structure study; precursor materials and energy account for approximately the 50% of CF costs; depreciation on CF can be potentially achieved by shifting from PAN precursors to natural fibers.

4.4. CFRP market studies:

4.4.1. General market volumes and producers.

CF market:

CF and CFRP market is primarily composed by energy related products; that is products consuming high volumes of energy in their use phase in which the strength to weight ratio of CF is truly beneficial.

CF market is commonly divided on Industrial, Consumer and Aerospace applications with the following divisions and volumes:

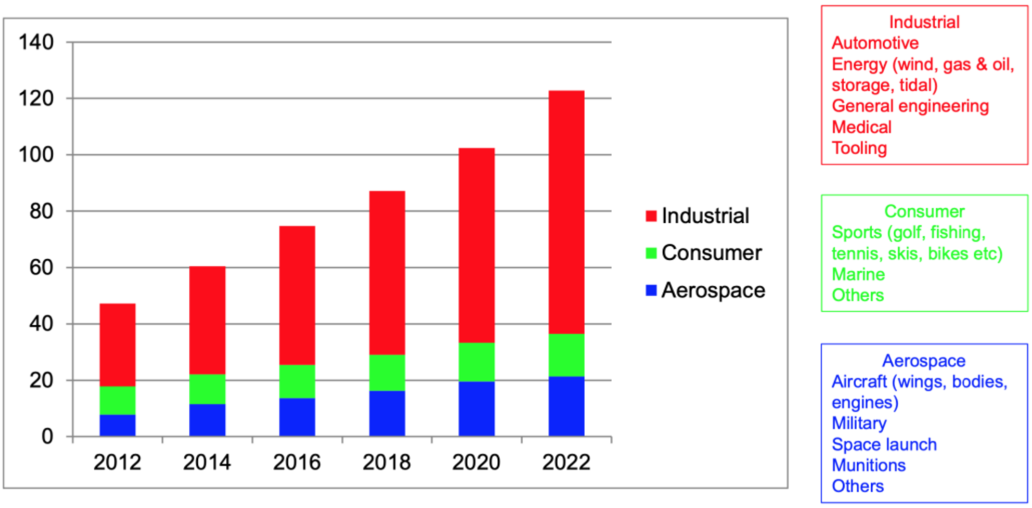


Fig. 52. Global use of Carbon Fiber (kTons) and main markets definition.[55]

CF producers:

Due to the high fixed costs and complexity involved on the production of CF; production is restricted to big manufacturers who can benefit from scale economies.

Toray industries is currently the biggest CF manufacturer, stablished in Japan. Toho Tenax is member of Teijin Group, a big chemical, pharmaceutical and information technology company also based in Japan. Zoltek is a subsidiary company of the Toray group since 2014; in its origins it was based on Missouri, USA, as an historic actor on the production of CF for the American space industry.

Mitshubishi Rayon, part of the Mitsubishi group is a major Japanese textile company that manufacturers chemicals, plastics and fibers in Japan.

SGL is the biggest European manufacturer in Germany, founded in 1992.

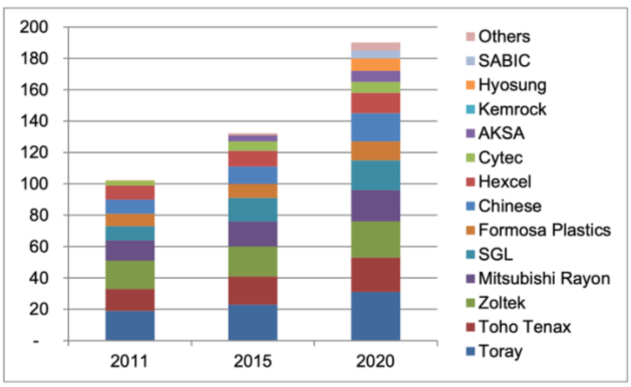


Fig. 53. Carbon fiber production kTon and major producers [57]

These great actors cover most of the CF market.

4.4.2. CF cost structure

The following chapter will depict the cost structure involved on CF production, CF cost have great repercussion on market adoption as will be explained on the following chapters:

Studies by N. Srinivas, P. Blanchard, D. Buckmaster, S. Davis et al[58] ; exposed a cost model for the production of carbon fibers contemplating the production of precursor fibers. In the following chapter a summarized view will be given.

CF Cost contributors:
Following table includes the cost contributors for CF production:

Item	Cost (USD) per Kg of PAN
Polymerisation to Coagulation	2.02
Energy	0.147
Labour	0.644
Water	0.0378
Sizing	0.0139
Depreciation	0.370
Final Packaging	0.0278
Insurance	0.0326
Tax	0.016
Filtration	0.0326
Waste Disposal	0.005
Total	**3.348**

Fig. 54. Cost of contributors for CF production.[58]

Costing study is performed by considering a 2140 tones per annum production line under the assumptions of state the art production technology.

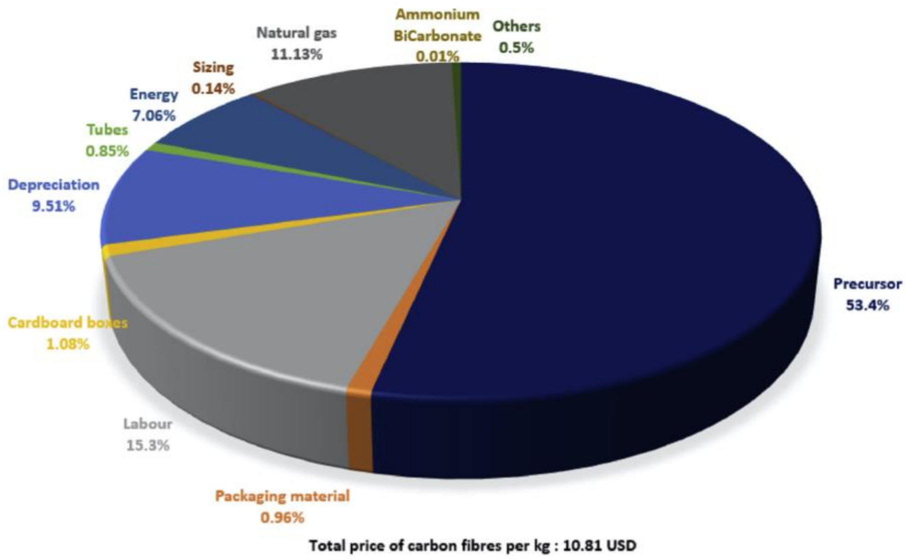


Fig. 55. Share of cost contributors on the total price of CF. [58]

<u>CF Cost sensitivity and reduction:</u>
The study stablishes a price of 10,81 USD/kg and the cost contributors; precursor fibers production is the highest contributor on price followed by labour and energy.

The study stablishes an inverse relation between tow size and CF price; as tow size and production capacity increases, labour cost reduces. Precursor price reduction is associated with the number of spinnerets and increase on efficiency in the thermal processes associated with greater lines. It must be taken into account that precursor fiber costs also include energy costs.

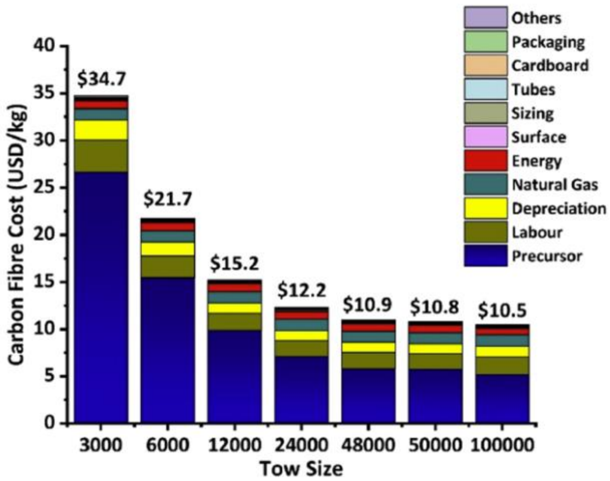


Fig. 56. Carbon fiber cost contributors depending on tow size [58]

Therefore the study proposes an increase in two size as a method to reduce CF costs.

4.4.1. Aerospace industry market.

[1] Fiber-reinforced composites to aircraft can be traced back almost three decades to the F-14 (US Navy) and F-15 (US Air Force) fighters which used boron/epoxy skins in their empennages. Since then, the use of CFRP in military and transport aircraft increased resulting for the experienced high performance.

Initial application to aircraft structures was in secondary structures such as fairings, small doors and control surfaces. As the technology advanced, the use of CFRP for primary structures such as wings and fuselages increased.

Aircraft industry chooses CFRP not only to reduce weight, but also because these materials are corrosion and, to a certain degree, fatigue resistant. The limiting factor in the widespread applications of these materials has been their high cost compared to that of the conventional metals.

<u>Fighter aircrafts:</u>
Percentage by weight of composite materials used initially was small at 2%, but has since grown to more than 24% for the F-22.

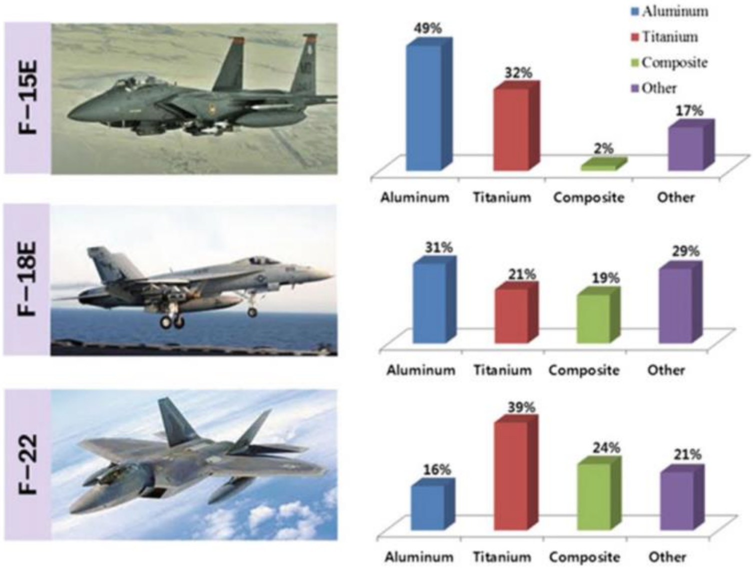


Fig. 57. Weight of composite materials on fighter aircrafts

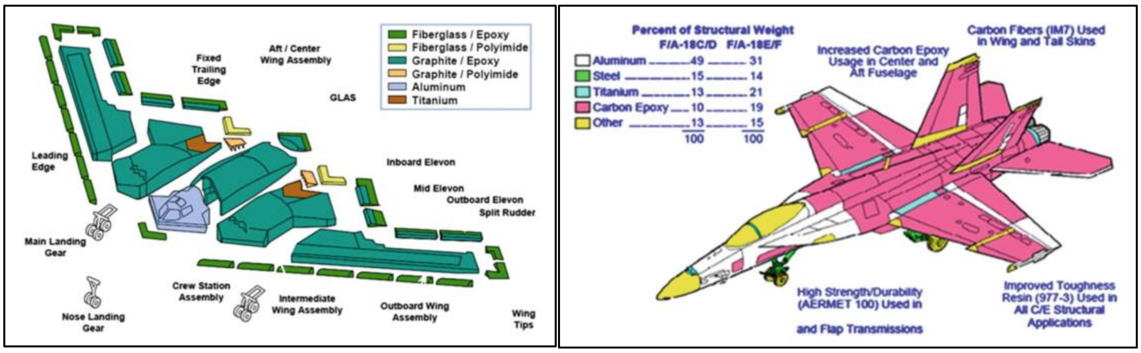


Fig. 58. Composite structures in B-2 bomber and F/A-18 E/F [1]

Transport aircrafts, Airbus:

Airbus initiated the use of advanced composites in the Airbus A300 aircraft which first flew in 1972. The composite material was then used in the fin leading edge and other glass fiber fairing panels. This employment has been growing through the years through kits and substitution of components to spoilers, rudders, airbrakes and landing-gear doors.

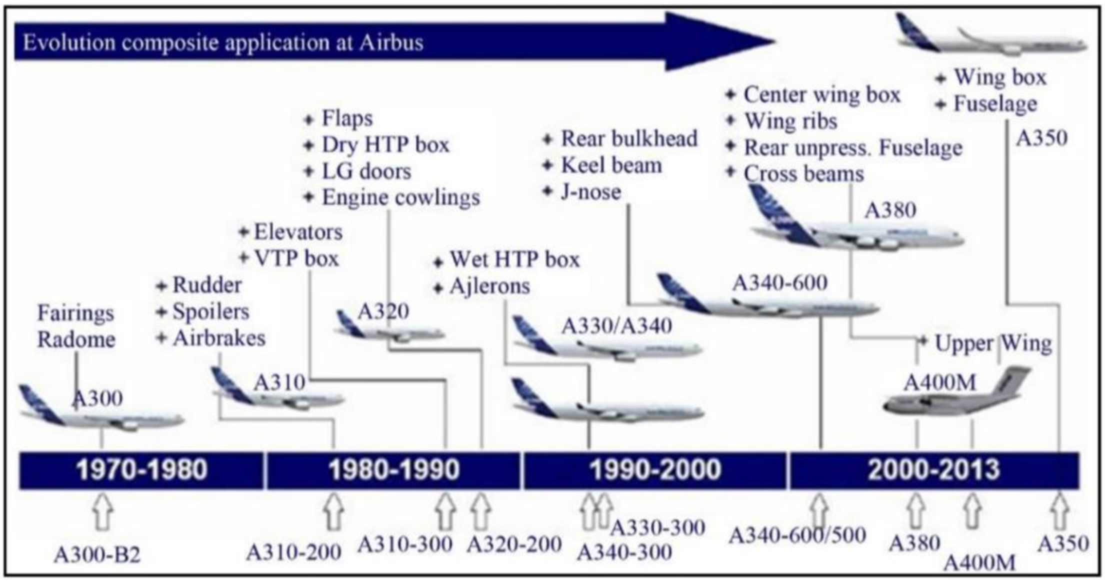


Fig. 59. Evolution of CFRP use in Airbus models through history.[59]

· Nowadays the composites account for approximately 15% of the structure of the Airbus A320 aircraft.
· The newest A350 employs up to 53% of composite materials:

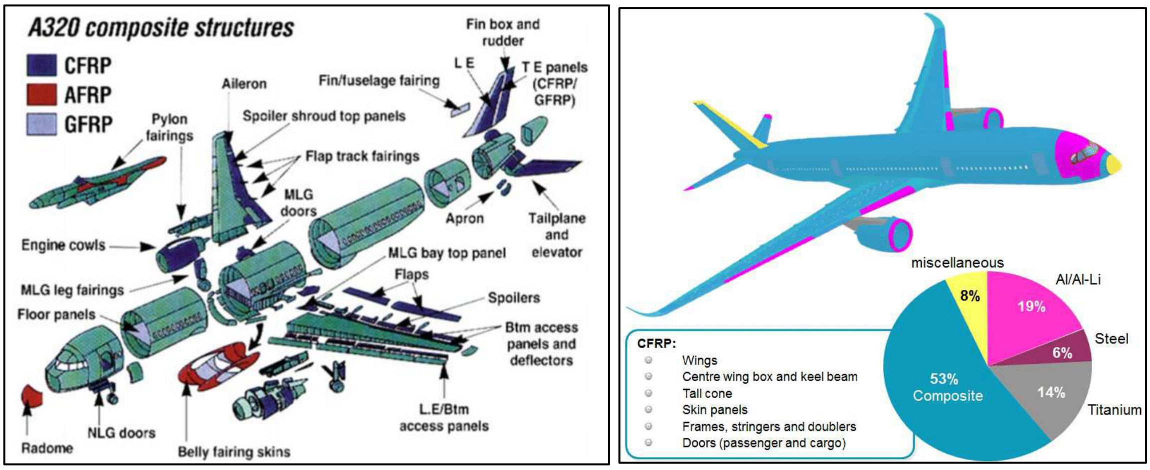


Fig. 60. CFRP employment on Airbus A320 (left)[1] *and AIrbus A350 (right)*[59]

The repercussion of the increase of CFRP structures in aircraft on the overall and worldwide CFRP market must be noted with the following agreed Airbus fleets:

Region	Start Fleet 2020	End Fleet 2041	Deliveries (2022-2041)	Remaining
Africa	610	1.490	1.210	280
Asia-Pacific	7.410	19.990	17.350	2.640
Europe/CIS	5.490	9.160	7.970	1.190
Latin America	1.360	2.710	2.540	170
Middle East	1.210	3.030	2.950	80
North America	4.770	7.480	6.580	900
World	**20.850**	**43.860**	**38.600**	**5.260**

Table. 9. Current and 2041 fleet numbers of Airbus models[60]

Transport aircrafts, Boeing:

[1]For the American major maker (Boeing), percentage of composites weight was as high as 20% since the Boeing 777 whose maiden flight was 10 years ago with materials used for the wings leading edge, trailing edge, flaps spoilers, landing-gear doors or floor beams as well as the empennage.

Recently launched Boeing 787 will average extensive use of composite materials (as high as 50%) in the quest for high efficiency and performance with reduced weight.

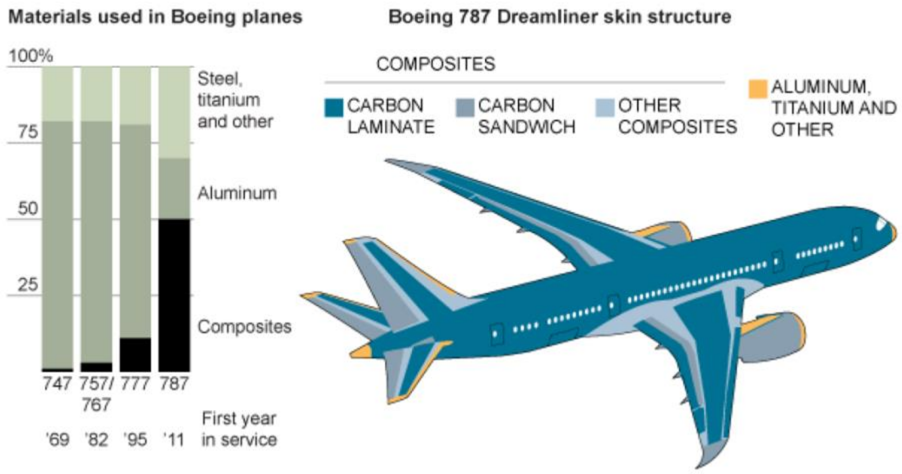


Fig. 61. Share of CFRP use in Boeing planes and 787 structures [61]

The repercussion of the increase of CFRP structures in aircraft on the overall and worldwide CFRP market must be noted with the following agreed Boeing fleets:

	737	767	777	787	Total
Total unfilled orders (2022 to 2041)	4.248	121	439	574	5.382

Table. 10. Boeing commercial market Outlook

Aerospace industry conclusions:

Aerospace industry has been a major CFRP consumer historically, in order to comply with new targets of fuel consumption affected by commercial objectives but also by governmental regulations. · As aircraft industry is overall growing and fleets are agreed to increase in the future; there is a precise link (made of the percentage of CFRP employed on each aircraft) that allows to predict CFRP market with growth expectations.

4.4.2. Space industry market.

Space industry has gained importance over the last years; with increases on traditional aerospace and government expenditure, but also in the new space economy which is defined as the private inversion on space activities; research from McKinsey [63] shows the global increase of space related R&D expenditures, in comparison with 2010.

New space:

Most new space market is related with "Earth services" (telecommunications), "space for space" transactions (such as in-orbit refueling services) and others related with tourism, space and materials sourcing.

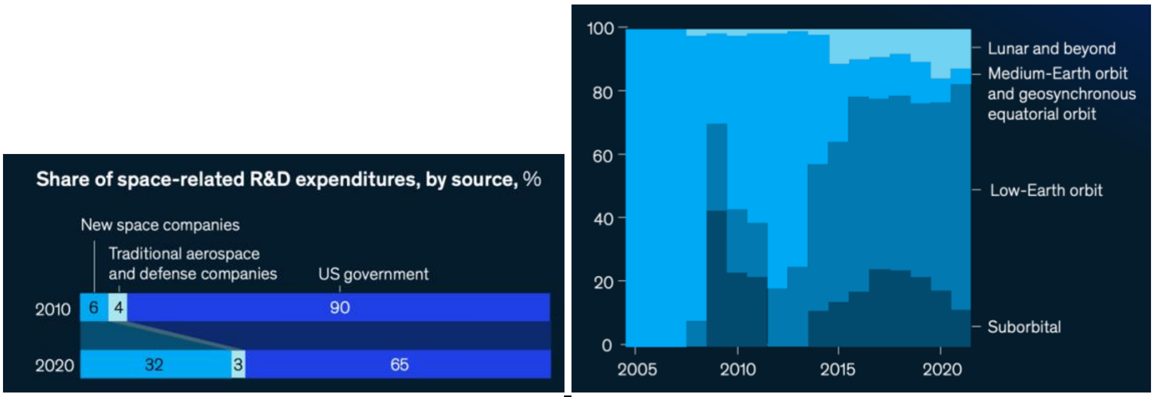


Fig. 62. Share of space-related R&D expenditure and yearly evolution

Most of the market is related with low earth-orbit activities, that is, related to satellites use, more precisely, private companies have exposed plans to launch over 70.000 satellites in the future.

Other activities related with low-earth orbit are related with the cleaning of space debris.

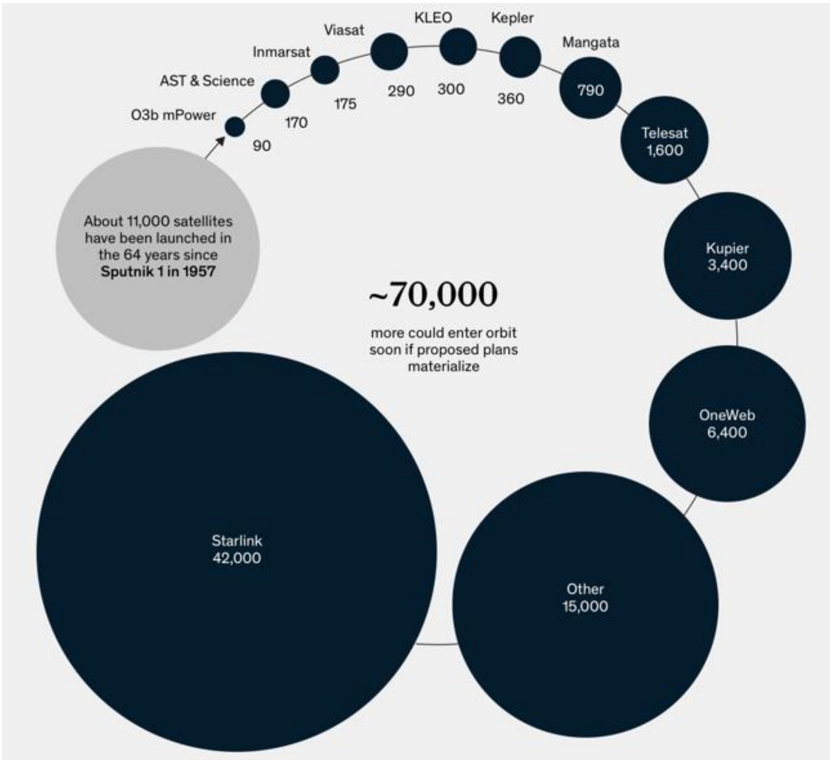


Fig. 63. 2021 Plans for satellite orbit by company [63]

Traditional aerospace industry:

Traditional aerospace industry has been historically a key actor on CFRP development on materials, mechanical characterization and applications. However, traditional space industry, governmental and currently focused on space exploration CFRP consumption is residual.

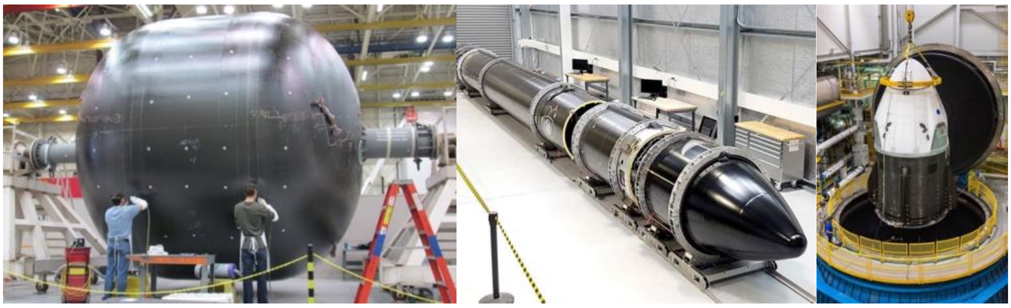


Fig. 64. SpaceX oxygen tank development on CFRP (left) [64], Electron two-stage rocket construction in CFRP (center) [65], crew dragon module (right) [64]

Space industry market conclusions:
CFRP products have been historically employed on the space industry and technology is critical for product performance on high strength materials and low weights critical on dimensioning space launches. New space economy has shown a great increase and prospects for satellite launch which depend on CFRP rockets; however, despite contributing to CFRP technology development, overall CFRP market is still limited.

4.4.3. Automotive industry market.
Initial approaches on CFRP employment on the automotive industry was tied to the needs of high performance premium vehicles as the mechanism to reduce vehicle weight to improve dynamics, the power to weight ratio and safety.

On average consumer vehicles, product price is critical for market success, CFRP high prices have been a barrier for adoption historically.

As European environmental regulations on vehicle emissions have evolved, new powertrains have been substituting ICE vehicles by EVs, FCEV (Fuel Cell Electric Vehicle) with special needs and weight issues; for ICE vehicles focus has been on weight and consumption reduction.

EV vehicles market:
EV battery cells impose a weight and battery range concerns; CF and lightweight materials appear as an opportunity to increase ranges with balanced costs (as CF substitution can be more economic than the costs from battery size increments).

CF has been employed for batteries enclosures that provide safety, adaptability and rigidity to vehicle structures; CF vehicle structures have been restricted to high end vehicles but in the recent years new approaches on structural vehicle design have emerged by the potential of CFRP to reduce the vehicle parts and providing production lines flexibility.

CFRP are also being adopted in the form of non-structural low grade materials by incorporating short fibers on thermoplastics on auxiliary non critical parts as a way to reduce weight.

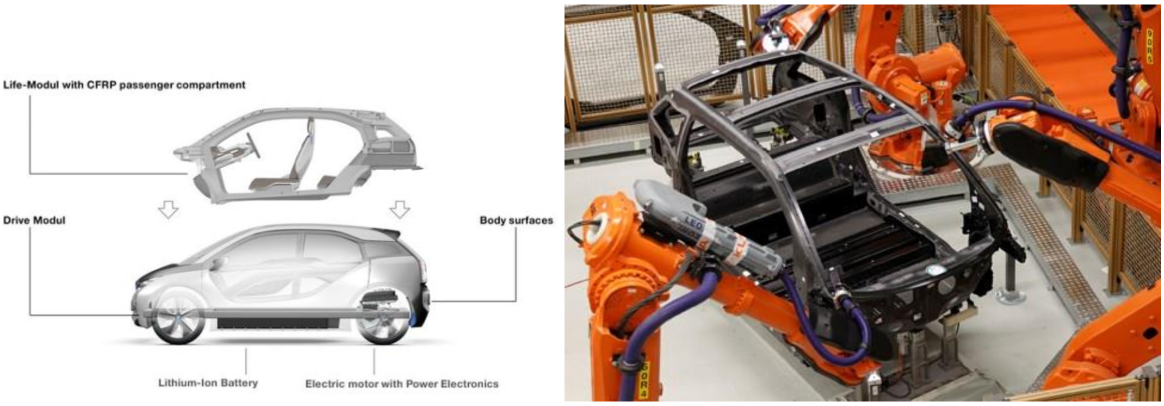


Fig. 65. BMW i3 CFRP passenger compartment structure and production [66]

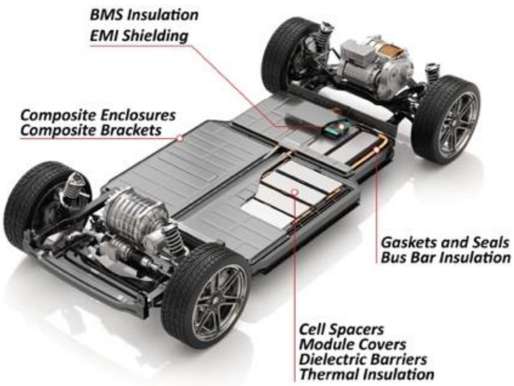


Fig. 66. CFRP battery enclosure and vehicle platform for EV [67]

More precise information of materials substitution on vehicles will be thrown on chapter 5.3.x. Strategic analysis.

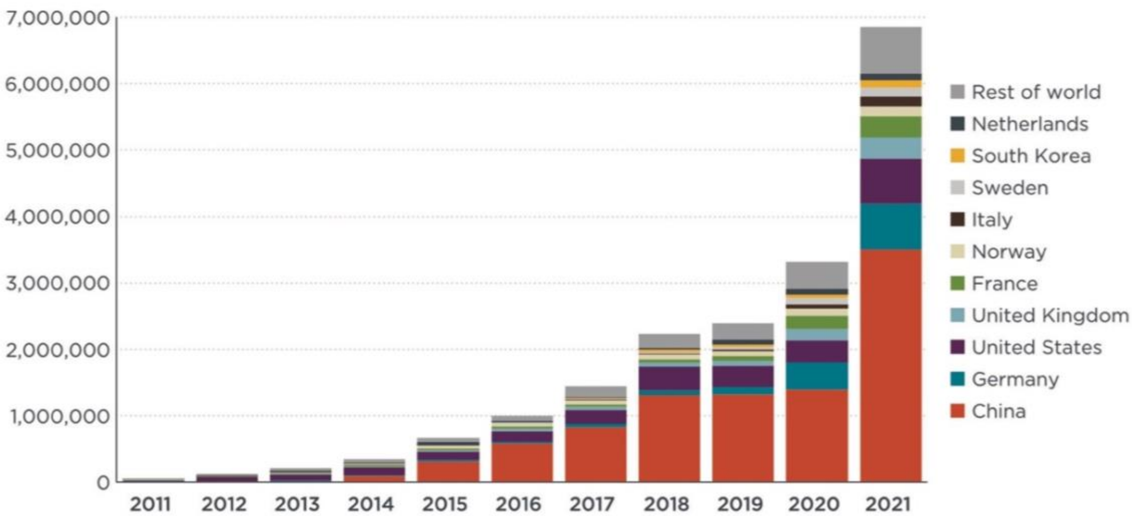


Fig. 67. Worldwide electric vehicle product sales, 2021 overall share of EV is 8,3%.[68]

As EV sells are expected to increase, so is CFRP consumption.

FCEV vehicles:

Fuel cell electric vehicles are powered by hydrogen, the energetic vector which is converted to electric energy on the fuel cell. This kind of powertrains needs of the storage of hydrogen at high pressures, with most adopted standards at 350 and 700 bar; pressure together with high volatility and energetic content, impose a challenge on security for the passengers.

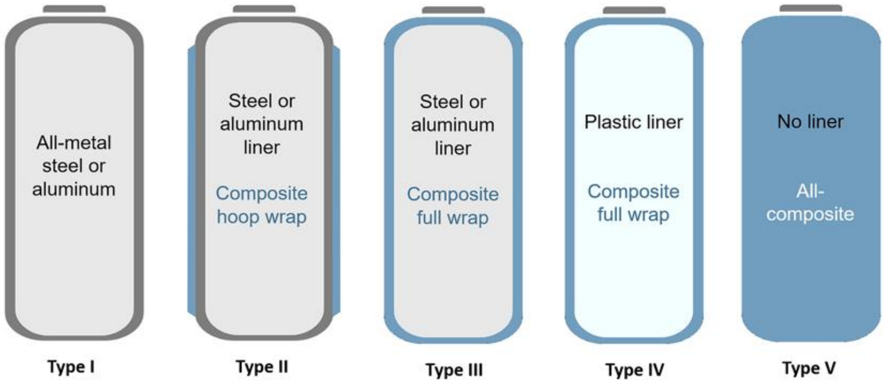


Fig. 68. Hydrogen tank classification [69]

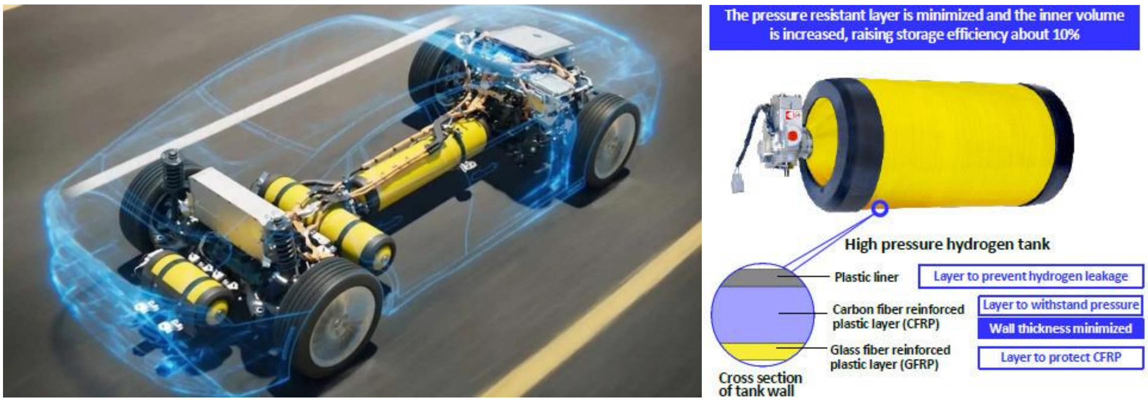


Fig. 69. Toyota Mirai storage and powertrain systems(left), Storage tank structure of the Toyota Mirai (right).[70]

As metal tanks are heavy and affect highly the energy consumption and vehicle dynamics; Type IV and V tanks (made completely by CFRP winding technology) are currently the leading choice for fuel storage and show great market potential in the future as FCEV have the potential to interact in a carbon free economy.

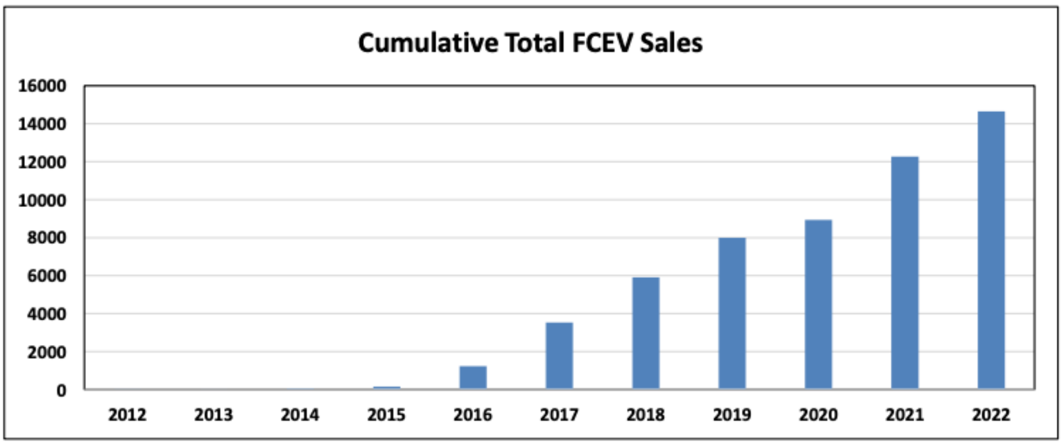


Fig. 70. Cumulative total FCEV sales.[71]

Automotive market conclusions:

· Emission restrictions have had a positive effect on CFRP employment and market.

· For ICE market, Europe has already announced end of sales for 2035, current employment of CFRP is driven to comply with emission targets by employing low grade CF products to reduce part weight in non-structural or non-critical parts.

· For EV market; CFRP allows to reduce weight and battery size in an economical way balancing the high battery cells costs; CFRP employed is commonly high grade applied on structural parts (passenger compartment or battery enclosure which also acts as vehicle platform).

· EV market sells are expected to grow involving higher employment of CFRP for battery enclosures and vehicle structures

· For FCEV market; CFRP is a technology enabler for hydrogen storage. As FCEV market sells are expected to grow, growth in CFRP tank technology is expected.

4.4.1. Wind energy market:

Studies carried out between the University of Warmia (Poland) and the University of Pennsylvania [72] show that Renewable energy has experience an increase in the recent years. More specifically the share of energy from renewable resources in Europe has almost doubled from around 8.5% in 2004 to 17% in 2017. The targets set by the EU.

Data compiled by Eurostat shows the evolution on the energy mix from renewable resources with almost linear growth.

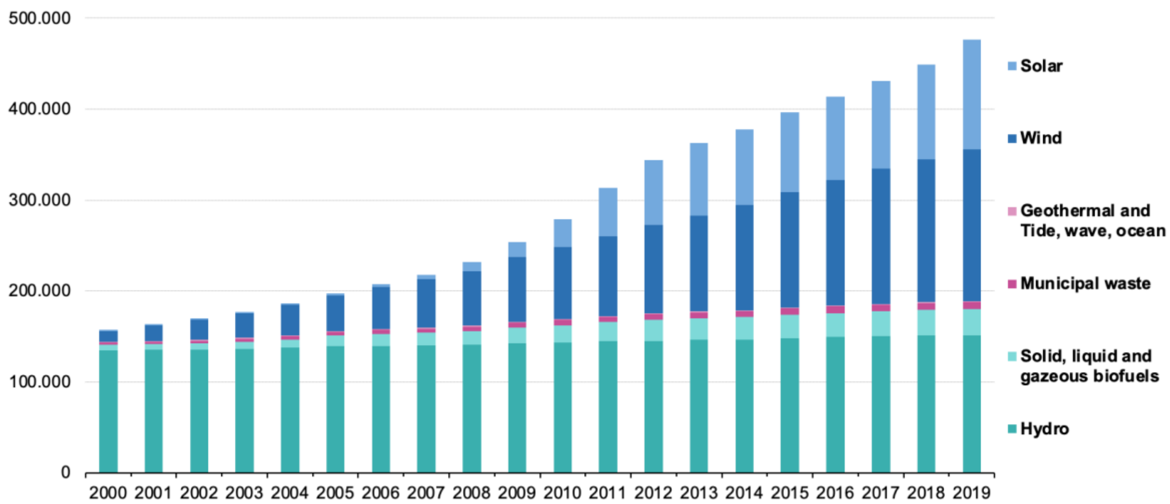


Fig. 71. Energy mix of renewable resources [73]

Evolution of wind energy capacity show steep linear increment on wind energy capacity, for the late and following years, it is expected that further wind installation will be offshore based.

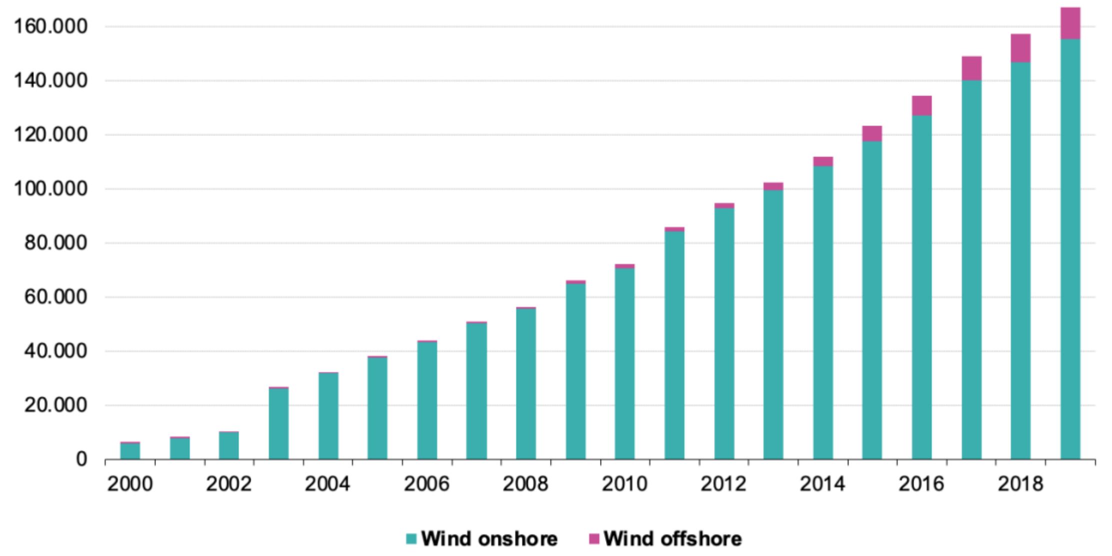


Fig. 72. Electricity production capacities for wind onshore and offshore in EU-27 [73]

Wind energy is a viable market for carbon fiber technology as an enabler to achieve higher energy outputs from generators. However, the use of CFRP structures is residual versus the glass fiber composites which present lower costs; CFRP structures will be only employed in high power wind turbines in which CFRP employment is critical and have an opportunity in offshore applications in which environment and mechanical solicitations are higher.

4.4.1. Strategic analysis, market drivers and barriers.

Following chapter summarizes the overall market drivers and barriers by identifying factors and trends on CFRP adoption as identified by strategic consulting firms.

Studies by McKinsey [74] expose that lightweight material have its greatest market employment on Aviation, Wind generation and Automotive Industries.

Market drivers:

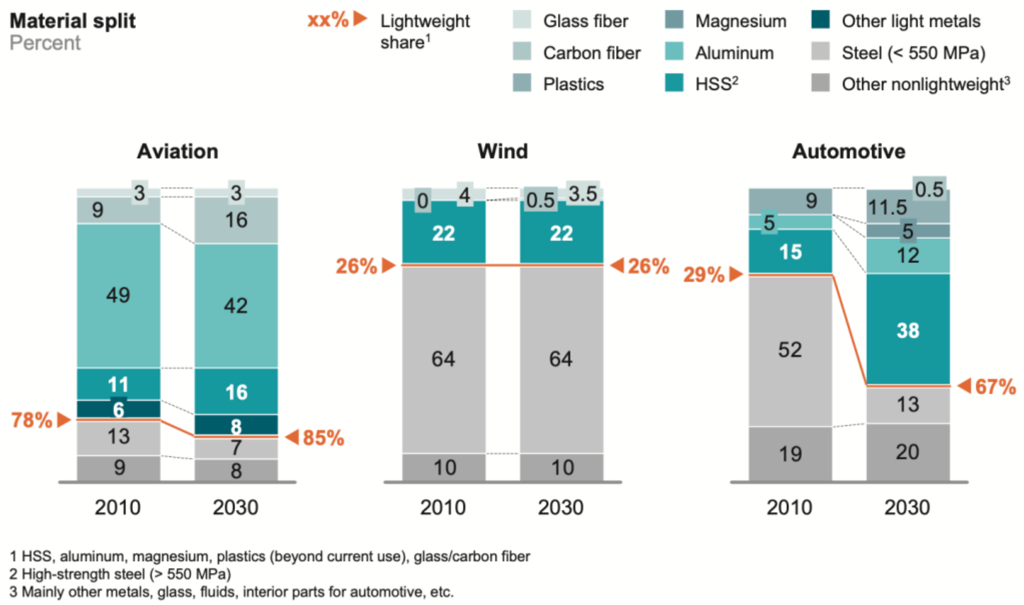


Fig. 73.Material shares on different industries and evolution [74]

Aviation Industries:

Lightweight materials use (such as light metals, aluminum, plastics and composites) build up roughly 80% of all materials use, significantly ahead of all other industries.

The use of lightweight materials in aviation has two main drivers:

· The need to reduce fuel consumption

· The wish to increase passenger/cargo load per flight.

New aircraft model, such as the Boeing 787 Dreamliner and the Airbus 350XWB have a significant share of carbon fiber (about 50 percent of the structural weight). This decisions as well as the expected growth of the industry overall (double the annual aircraft deliveries in 2030 compared to 2011) will lead to strong growth in the carbon fiber market (from 8.000 to 40.000 tons).

Wind industries:

Extreme lightweight materials are applied on the long rotating blades which transform the wind energy into rotating energy that is then transformed into electricity. Due to the high wind speeds and the size (length and mass) of the blades, the blade material has to bear high stress, which can be reduced by using extremely light materials. Currently, most wind turbine manufacturers use glass fiber as structural material for their blades.

Two of the industry's big players are already using carbon fiber because it is stiffer than glass fiber. The stiffness factor of carbon fiber allows to further increase blade length that cannot be achieved with glass fiber, resulting in greater output per wind turbine.

Besides, wind turbine installation in 2030 is expected to be four times that of 2011.

The use of carbon fiber in the wind industry has two main drivers:

· The wish to increase power output in wind turbines

· The expected growth for the wind turbine installation in land and off-shore

Automotive industry:

Automotive industry has been paying attention to vehicle weight for decades since it has a direct impact on driving dynamics, agility and fuel consumption. The use of costly lightweight materials has been limited by the consumers limited willingness to pay for weight reduction.

The introduction of CO_2 emission targets and penalties has reignited interest for weight reduction as a lever to minimize fuel consumption.

Lightweight measures help reduce CO_2 emissions with approximately 0.08 g CO_2 /gm per kilogram saved. However, this materials in combination with internal combustion engines (ICEs) is not sufficient to reach CO_2 targets for 2025. OEMs will push electric cars with an increase in system weight and cost , lightweight materials are needed to reduce impact on additional system costs for electrification.

Extremely high penalties (EUR 190 per gram and car sold in the next decades) failing to meet the CO_2 targets is not an option for OEMs since all the penalty per car sold could amount to more than EUR 12.000.

The use of carbon fiber has the following drivers:

· Reduce consumption to achieve CO_2 emission targets

· Reduce EV system costs by light weighting

Following figure shows percentage of materials use in the three mentioned industries.

Market barriers:

CFRP cost:

Various lightweight materials are in use such as high strength steel, plastics and aluminum. With penalties on CO_2 generation, use of lightweight materials delivers monetary benefit on the automotive industry. In aviation industries, fuel consumption is greatly reduced and passenger/cargo are increased; in wind energy, savings are produced on the long term by higher power outputs.

Carbon fiber has the greatest potential for weight reduction but costs are enormous (five to six times as high as steel, assuming a mass production of 60.000 units per year) and prohibit high penetration on the market.

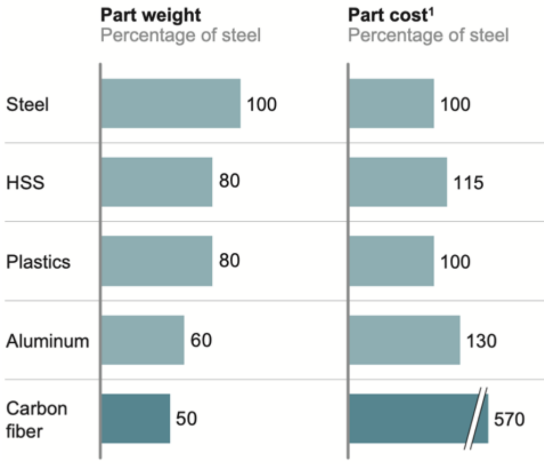


Fig. 74. Relative part weight and cost of CFRP and other lightweight materials [74]

Cost evolution on CFRP:

For the next two decades, it is expected to observe a significant cost decline for automotive carbon fiber applications, from about 42eur/kg today down to 23eur/kg in a conservative cost scenario.

The projected carbon fiber cost decrease will be mainly driven by:

1. The development of a less expensive precursor material to produce the carbon fibers (textile PAN precursors or even lignin-based precursors instead of oil-/gas-based precursors to decouple the material price from oil price) resulting in a 30 to 50 percent cost decrease for the raw material.

2. A reduction in the processing cost for pre- and part forming of 60 to 80 percent due to radical reductions in cycle time driven by, for example, the development of fast-curing resins and the resulting reduction of investment and labor costs per part.

This fall in cost will bring carbon fiber significantly nearer to comparable to aluminum parts though a difference of 20 to 30 percent will remain. Carbon fiber, additionally, offers a greater degree of freedom in car design and performance.

Industrialization hurdles:

Despite the significant weight reductions, the high cost is the key obstacle to broad use of this material. In addition to the high cost, several other challenges are often cited, which are to be overcome in time.

Three main challenges beyond carbon fiber's cost are maintenance and repair, sustainability/recycling and simulation:

· EU legislation sets a target of 85% recyclability for vehicles, than CF recyclability is core to its potential success. Many efforts are under way to address this challenge and promising results begun to surface.

· Maintenance of CF parts is difficult since damage can often not be seen through visual inspection and detection requires acoustic emission, thermal, ultrasonic or x-ray imaging. These involve potential investment costs. In terms of repair, many method already exist on aviation industry, such as bolted or bonded repair which can be transferred to automotive industry. Internal delamination can be repaired by injecting resin if the damage affects a nonstructural, only-local part.

· For crash simulation, advancements produced on the aviation industry can be transferred, limitations in crash simulations still exist today due to the anisotropic behavior of the material. Simulation programs allowing for the prediction of this material will be developed over the coming years.
· Extremely high energy consumption involved in carbon fiber production, bearing the risk of an overall negative CO_2 impact depending on the energy mix used

<u>Trends in materials use:</u>
Higher performance materials will gain market versus steel, for carbon fiber, it is expected a 17% CAGR increase from 2010 to 2030.

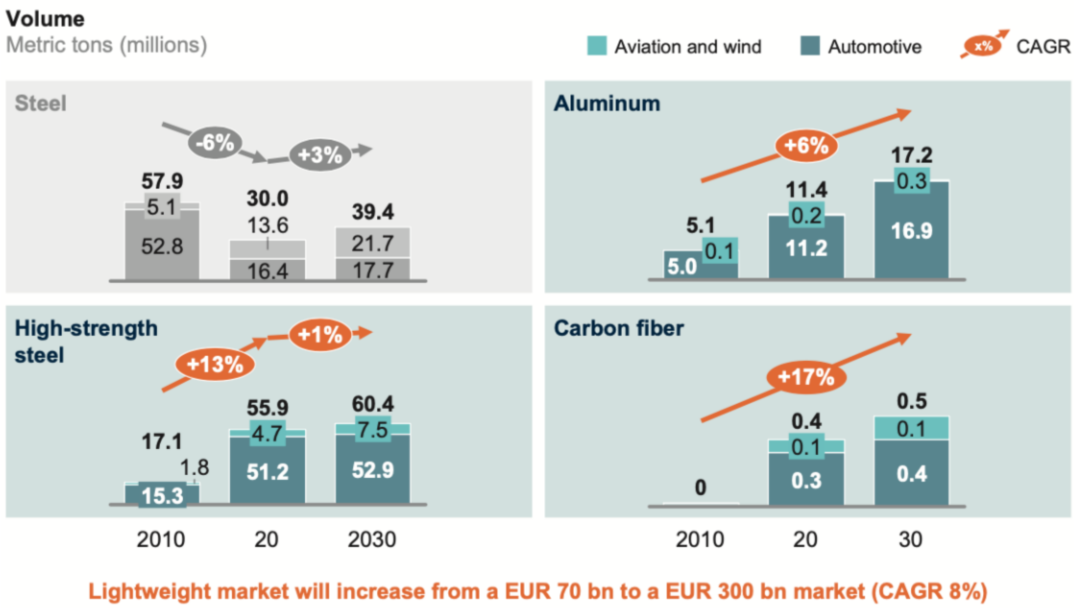


Fig. 75. CAGR (Compound Annual Growth Rate) of lightweight materials.[74]

4.5. CFRP market forecasting

For market forecasting, statistical time-series analysis techniques will be employed. Time series analysis is applied to measures taken in respect to time, that is, listed in time order taken on equally spaced points in time.

This type of series allow for specific kind of modelling and analysis techniques.

As the techniques are based on the data inputs; forecasting will be strongly tied to market data. As exposed on the objectives of the project, it is expected to generate a 5 year forecast.

Initial data inputs (historical) has been obtained from the official reports of TORAY Industries; this manufacturer is the only one exposing data on a quarter year based with open-access information. Therefore, forecast produced only accounts for expected sales for the TORAY group; results, although not covering the whole market can be translated to other producers and show an analysis and high level forecast result for the future.

Modelling techniques:
An ARIMA model will be employed to fit and predict data values on the future.

As ARIMA techniques allow for multiple hyperparameters to be adopted (number of terms of the Auto Regressive and Median Average models), an iterative search will be applied in order to optimize fitting.

Prediction intervals will be produce by RMSFE (Root mean squared forecasting error) calculated on test sets.

Initial data analysis:
Data is provided on the Annex I. Data Tables.

Initial data analysis reveals presence of high stationarity, caused by the quarterly compiled sells data with period 4. Data also exposes trend which is irregular, and apparently cannot be modelled by a linear model or quadratic. It can also be seen that trend is not affecting periods in the same way, being the period 1 less affected by trends.

Time series has 56 points compiling TORAY industries sales from 30June2009 to 31/12/2022 originally.

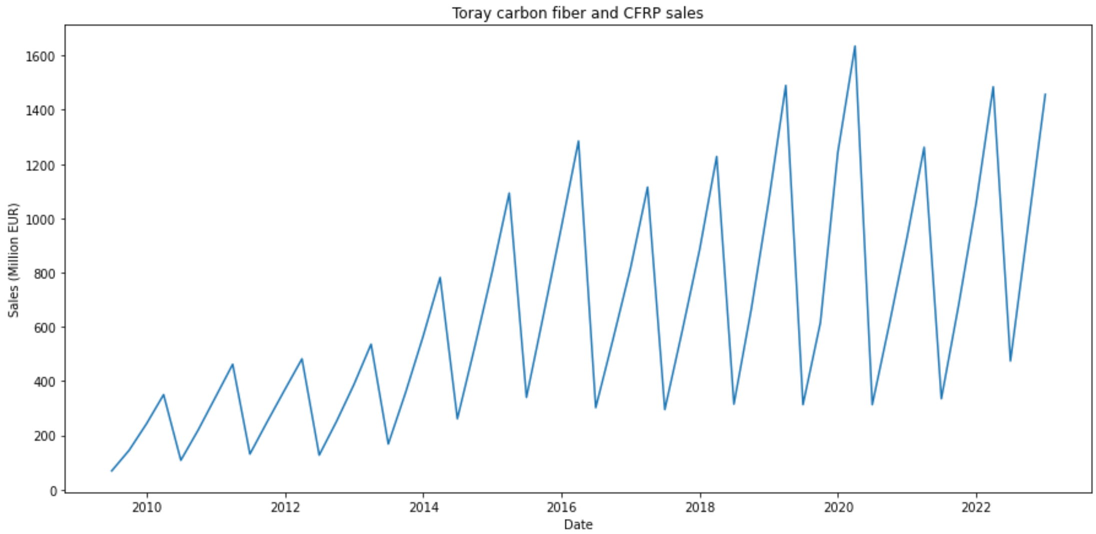


Fig. 76. Series plot of TORAY industries versus time, Sales are presented in million Eur.

<u>Rolling statistics and stationarity studies:</u>
As ARIMA model needs stationary data, stationarity studies will be performed by rolling statistics and Augmented Dickey-Fuller Tests:

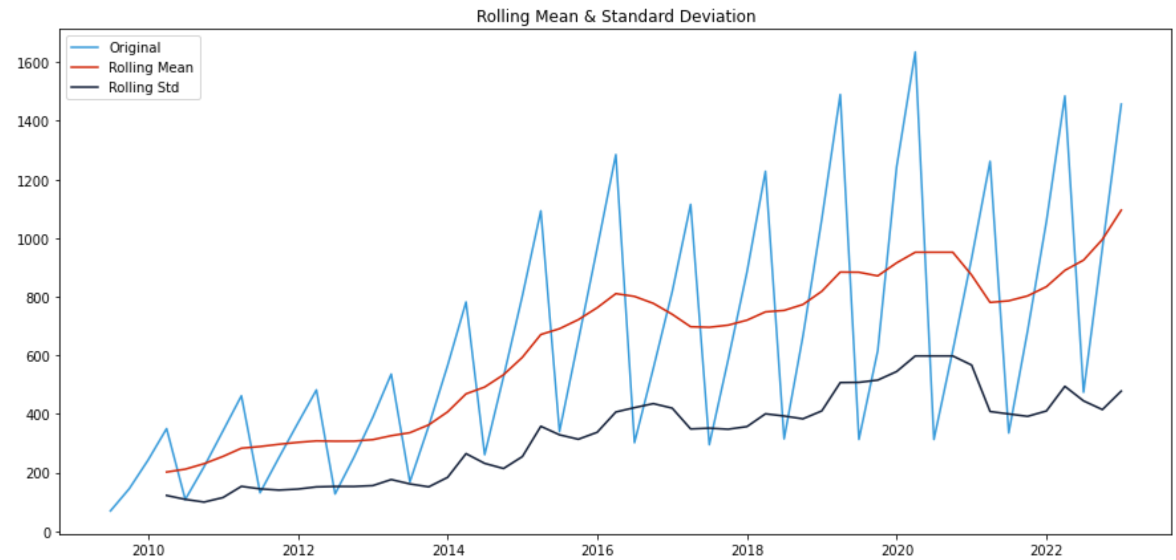


Fig. 77. Rolling mean of sales data and Std deviation of Toray sales data

Rolling mean exposes trend in data, which is not stationary.
Dickey-Fuller test results exposes test statistic below the p-value stating data as non-stationary.

```
Results of Dickey Fuller Test:
Test Statistic                  -1.010011
p-value                          0.749596
#Lags Used                      10.000000
Number of Observations Used     44.000000
Critical Value (1%)             -3.588573
Critical Value (5%)             -2.929886
Critical Value (10%)            -2.603185
```

Table. 11. Dickey Fuller test statistics of the Toray sales data

This fact implies the need to differentiate terms, that is, subtract past values from data in order to eliminate the trend (I term in ARIMA).

<u>ARIMA model selection and diagnostics :</u>
ARIMA model is fitted with order 4,2,1 (4 = p = autoregressive terms, 2 = d = degree of differencing, 1 = q = moving average terms)

Diagnostics below show the uniform distribution of residuals versus the time, the normal distribution of the residuals, correlogram checks the correct differencing order.

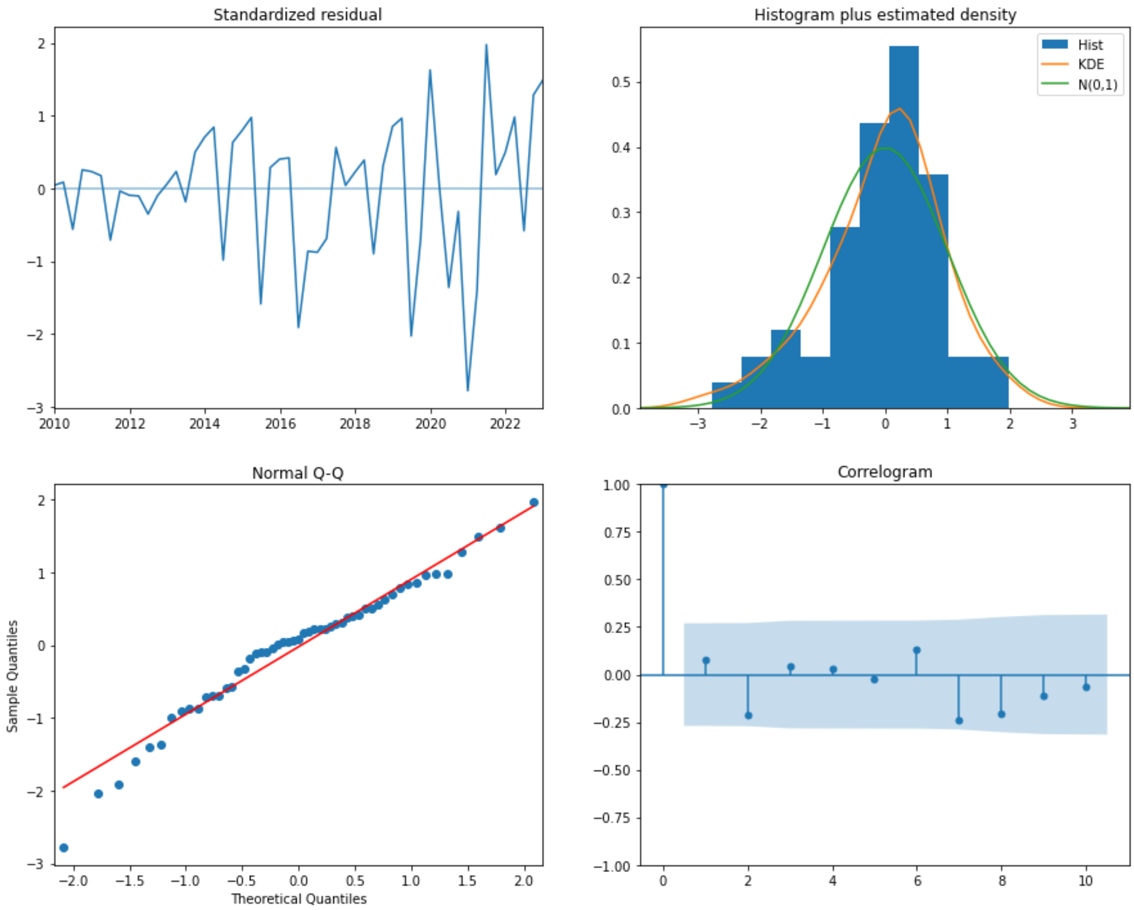


Fig. 78. Diagnostics of the model.

<u>5 year prediction:</u>
A 5 years forecast is produced; overall analysis reveals an increment on CF sales.
Taking end of 2021 (last closed exercise) as reference, we find:

31Dec2022 sales: 1057 Million Eur
31Dec2027 sales: 2252 Million Eur

That is approximately, to double the sales in a five year period.

Most negative forecast exposes that 31Dec2027 sales are 1261 Million Eur, still improving in a 20% increase the last closed exercise.

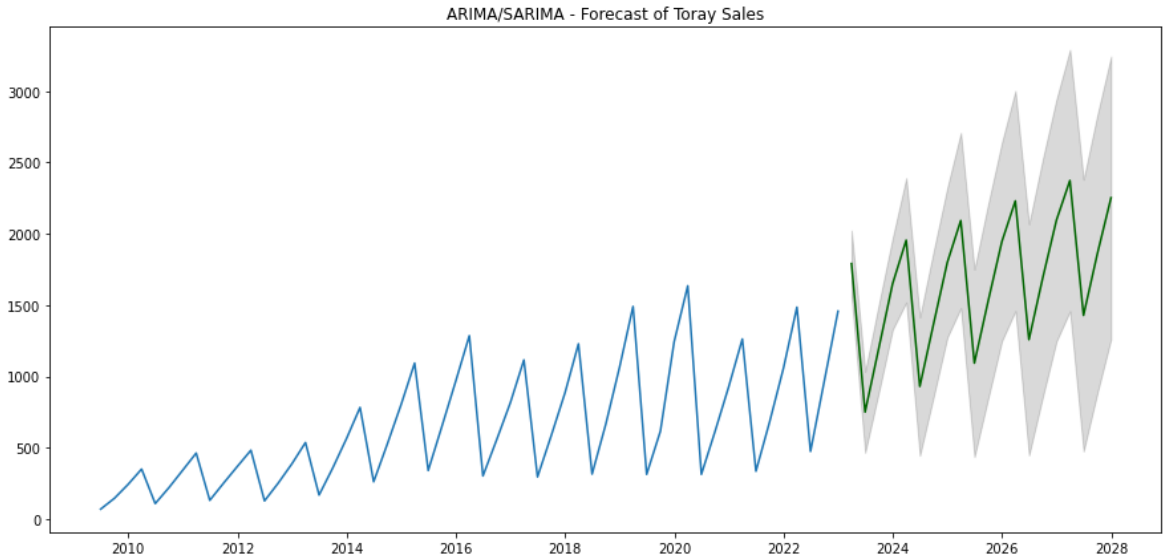


Fig. 79. Forecast of Toray sales from Dec 2022 to Dec 2027 and confidence intervals

<u>Conclusions:</u>
Time series data analysis shows growth forecast expected on the sales of TORAY Industry group even on worst case conditions with a 20% increase in sells un 5 years.

Taking into account competitiveness between CF producers it can be estimated that overall CF sales are expected to grow in the following years.

4.5. CFRP market forecasting open data

CF sells market data and forecasting has been compiled in open access Jupyter notebooks and CSV files.

Data and Jupyter notebooks for market forecasting can be accessed through the following link:

[CFRP market forecasting repositories]

5. Budget summary and/or economic feasibility study

As the developed thesis is in form of a study; budget is based on the professional fees of the engineer carrying out the study stablished in agreement with engineering/consulting salaries in Spain. Detailed budget breakdown is included in the Annex II. Project Costs.

The total cost of the study performed consists on **8.679,02 €.**

6. Analysis and assessment of environmental and social implications

The thesis developed includes the environmental assessment of the CFRP technology (4.5. CFRP Environmental aspects) and exposes a critical point of view remarking high energetic costs of CF manufacturing and the problems concerning the CFRP end of life.

However the study states CFRP as an enabler to lower energy consumption during *use phase*s in applications such as automotive or aerospace in which fuel consumption is directly related with the system's weight.

Social implications of the study are considered minor; exposing technical and market data. Some positive aspects are that open access datasets have been producing including technical and market information; the study here developed has also formative objectives helping open access to a specific field of engineering which have been associated with private training and costs.

An special effort has been put on the raw data origin identification as well as in referencing complementary publications and information for transparency purposes.

7. Conclusions of the study

Partial conclusions of the analysis performed have been exposed on the different chapters of the study. In the following chapter general conclusions will be drawn:

Technology study:
· CFRP is an exceptional engineering material with exceptional mechanical properties, however it cannot compete with metallic materials in thermal demanding applications. CF costs are higher above metallic or GFRP materials, then CFRP employment is reserved for niche applications in which high performance outperform acquisition costs.
· CFRP manufacturing is complex with many variables affecting the processes and designs; CFRP part production costs are elevated when compared with plastics or metal materials; however CFRP methods and designs allow for flexibility and freedom in short productions which can make them CFRP use more approachable than plastic or metal construction reducing the machinery investments.
· CFRP designs are also complex to produce when involving structural applications; anisotropic behavior requires to non-standard mechanical models and methods. Design weight optimization or design for failure are also challenging; most advanced software can facilitate design and analysis merging FEM methods and specialty composite design methods with guided workflow making these tasks more accessible to engineers.
· CFRP employment faces environmental challenges; CF production energy intensity is high, LCA assessment reveals that CF only outperforms other engineering materials in *use phases* in applications where energy consumption is highly dependent on weight. Thermoset matrices and high dependency on fiber length make recycling and maintenance of mechanical performance difficult; recycling methods have been developed recently improving energy consumption and recovered fibers quality. Recycling methods have the potential to allow multiple life cycles reducing the high energy involved in CF production and are expected to be developed as CFRP technology is more widely adopted.

Market study:
· European environmental restrictions have been critical for CFRP materials adoption as an enabler technology that saves energy in the transport sector and which allows for high performance in energy generation. Union political roadmap and funding is currently prone to facilitate CFRP adoption and development in many sectors.
· CF production is commonly based on Polyacrylonitrile precursors which need of petrochemical raw materials, therefore, CF costs are tightly tied to the oil market prices. PAN CF is related then to a non-renewable resource. Natural substitutes employed as CF precursors are far from PAN performance and expose low technological readiness.
· Aerospace industry has been a key stakeholder for CFRP development and adoption as weight reduction has great effects on flight costs. CFRP material share employed on the aircraft exposes exponential growth and growth of air transport ensures CF market.

· Space industry has been the initial adopter of CFRP technology; despite that space exploration involves a minor quote of CFRP use, the new space economy involves a large number of satellite launches with CFRP rocketry.
· Automotive industry as recently put great effort on CFRP adoption motivated by the EU regulations on decarbonization involving great market volumes. Fossil fuels will be banned from 2035, electric vehicles need lightweight materials to increase battery range, otherwise more expensive and greater battery packs would be needed; FCEV vehicles need hydrogen pressure vessels, filament winded CFRP tanks have shown great performance and security under low weights versus metal alternatives involving great energy savings.
· Wind energy production is also subject to potential CFRP usage; current wind turbines are produced in GFRP with great cost-performance; however higher power wind turbines require low weights and high stiffness for correct stability, structural and fatigue resistance with balanced cost outputs. Offshore wind energy installation plans involve high power wind turbines and extreme working conditions in which CFRP can outperform GFRP.
· It must be highlighted that CFRP employment and market success is conjunctural in a context in which CFRP technology is the only technology enabler to achieve higher efficiency ceilings; other material developments, technologies or approaches can outcompete CFRP employment. CFRP employment is also currently dependent on oil and material crisis can affect its adoption.
· For CFRP market forecasting raw data allowing the study is limited to a major CF producer, the ARIMA model fitted shows good performance and produces 20% growth forecasts even on worst case scenarios.

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