Analysis of the light weight fiber reinforced plastics value chain with regard to the German industry in its global context

Working paper to the project on "Low-Carbon Vehicle Futures for Germany"

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List of abbreviations

AL	Aluminium
BIW	Body-in-white
BMC	Bulk molding compound process
CAGR	Compound annual growth rates
CC	Carbon composites
CEMAC	Clean Energy Manufacturing Analysis Center
CF	Carbon fiber(s)
CFRP	Carbon fiber reinforced plastics
FRP	Fiber reinforced plastics
GFRP	Glass fiber reinforced plastics
GHG	Greenhouse gas emissions
HSS	High strength steel
LCA	Life-cycle assessment
MG	Magnesium
NFRP	Natural fiber-reinforced plastics
ORNL	Oak Ridge National Laboratory
PAN	Polyacrylonitrile
RTM	Resin transfer molding process
SMC	Sheet molding compound process
VDI	Verein Deutscher Ingenieure e.V.

1 Introduction

The automotive world is on the verge of a great transition. Assisted and fully autonomous driving, new mobility services, partial and full electrification of the drivetrain as well as the demand for sharp reduction of pollutants, energy demand and greenhouse gas emissions shape this transition.

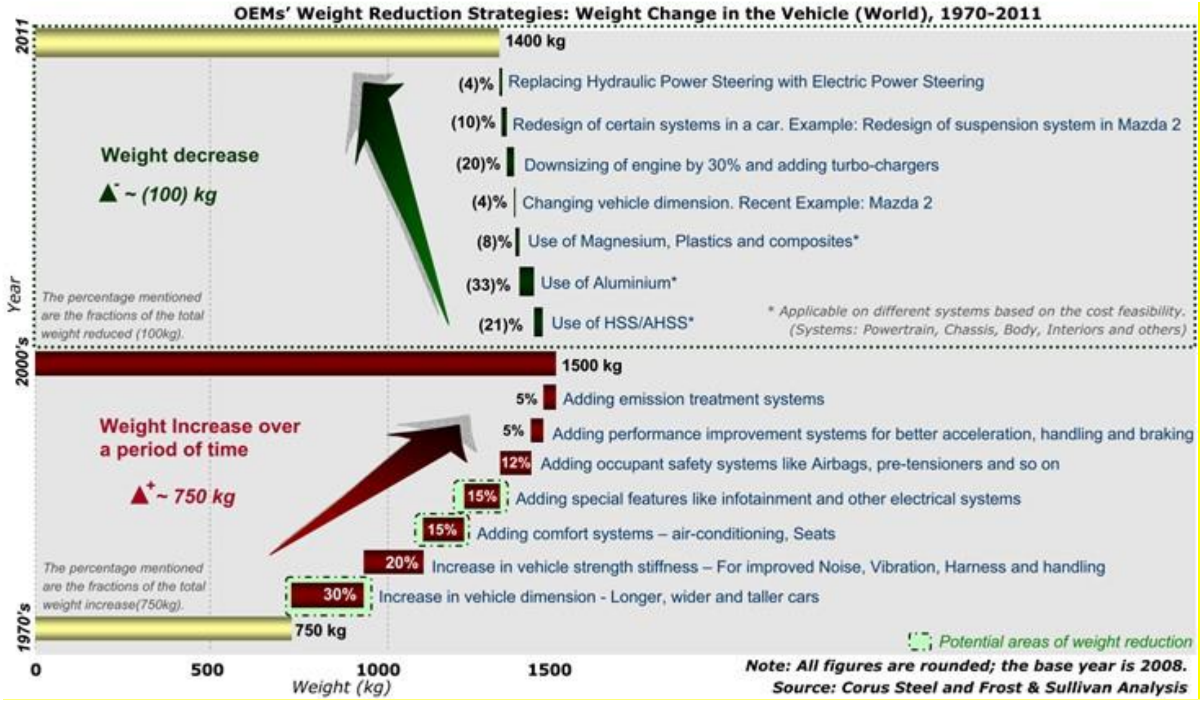
Lightweight construction is an approach to address several of these issues at the same time. Reducing the weight of a vehicle decreases the energy required to propel and in particular to accelerate it. Estimates of fuel savings of cars per 100 kg of weight reduced amount to between 0,2 and 0,5 liter of fuel per 100 km of travel. The requirement for saving energy by lightweight construction does not only hold for cars, but also for other road vehicles like buses or trucks and also for railways, metros or trams. For airplanes lightweight construction is a must anyhow. Therefore lightweight construction constitutes a cross-cutting technology, for which improvements in technology will bear fruits to reduce energy demand of several transport means. Technologies that have been developed for air transport in the past are transferred to cars today and may be applied in trucks and railways in the future.

In vehicles using fossil energy the consequence of reduced energy demand by lightweight construction will also be decreased greenhouse gas emissions. Vehicles using limited energy carriers like biofuels moderate the demand for scarce biomass. For electric vehicles that are facing the issue of limited driving ranges due to limited battery capacity lightweight construction is reducing the requirement to install costly and heavy batteries for energy storage. This includes applying lightweight construction also for the Lithium battery packs of electric vehicles themselves.

Though lightweight construction is an issue for all land modes and for air transport there are various approaches for the different modes differing in cost and performance. The focus of our analysis in this paper is on lightweight construction for cars.

Figure 1 presents the weight development of an average car since 1970. Between 1970 and 2000 the average weight has roughly doubled from 750 kg to 1500 kg. Major drivers were the increase of vehicle dimensions with 30%, the improvements of comfort and safety with together more than 60% due to vehicle stiffness reducing noise and vibration (20%), safety improvements like airbags (12%) and comfort systems like air conditioning, infotainment, etc. (30%) (Frost & Sullivan 2009, see also Grillitsch, 2013).

Since 2000 and until 2011 the average car weight has reduced by about 100 kg. Compared to the weight increase of 100% before 2000 the moderate reduction by about 7% indicates that the process of weight reduction requires careful and integrated planning and substantial efforts by OEMs and their suppliers. More than 60% of this weight reduction until 2011 came through the use of alternative materials: high strength steel (HSS) (21%), Aluminium (33%), Magnesium and Plastics (8%). Changing the design contributed most of the further reductions either by downsizing engines, vehicle design or redesigning system components. The abovementioned drivers of electrification and improving environmental performance ensure that these observed trends of increased use of lightweight construction will continue.



Source: Frost & Sullivan 2009

Figure 1: Trend of weight developments of cars over four decades, 1970-2011[1]

Following this introduction the working paper is structured into six sections. The first section briefly presents an overview on materials used in a car and on different options for light-weight construction. The following section discusses in detail the characteristics and the value chain of the major growth option of fiber reinforced plastics: carbon fiber reinforced plastics (CFRP). A brief section on glass fiber reinforced plastics (GFRP) explains the differences with CFRP. Since, raw materials play an important role in particular for CFRP a section on recycling of raw materials is added. Finally, a section on criteria to decide on production locations of CFRP is presented followed by a section on potential scenarios for future configurations of the value chain of FRP to be used for the project on Low-Carbon Vehicle Futures for Germany. A think piece is completing this working paper.

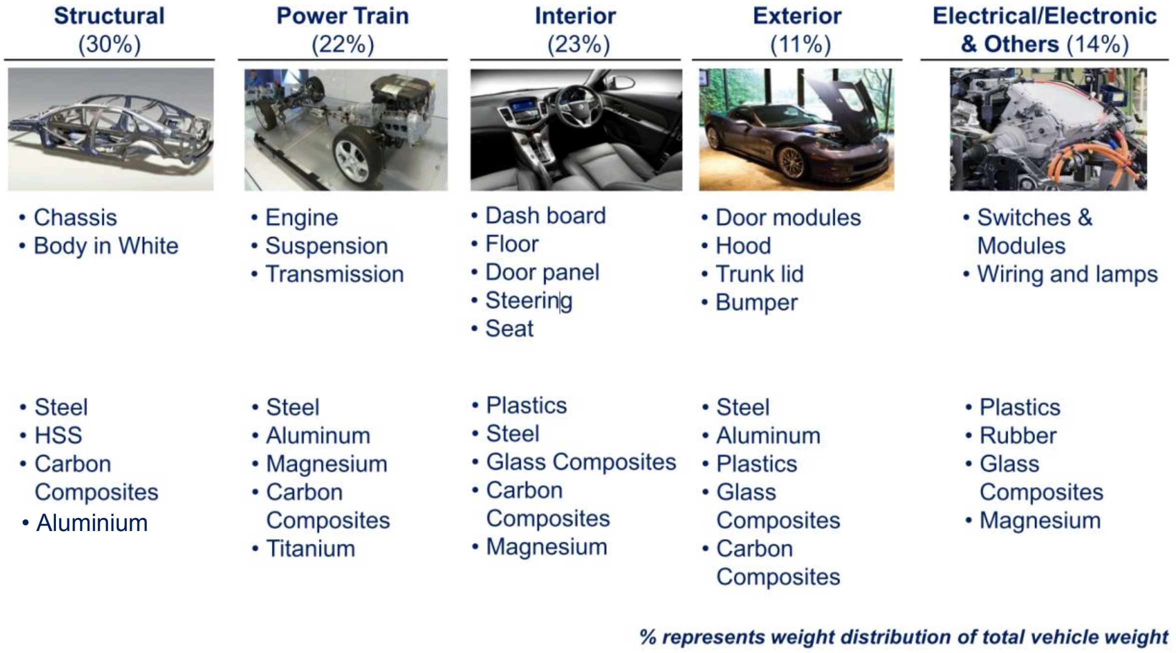
2 Lightweight options

Lightweight construction can be achieved by two basic approaches: (1) use of lighter materials, and (2) modification of the product structure to reduce the amount of material needed. This paper focuses on the use of lighter materials. Nevertheless, using lightweight materials often requires modifying structures as well.

Figure 2 presents the share on total vehicle weight of different major components. The structural components account for about 30% of the vehicle weight, of which the body-in-white (BIW) weighs about 300 to 350 kg in case it would be made out of steel. The whole power

[1] For Europe the Statistical Pocketbook of the ICCT reports an average weight increase from 2001 until 2007. Since then a kind of stagnation of average weight can be observed though in some years average weight was reduced while in others growth of weight occurred (ICCT 2015).

train makes up 22% of the weight, the interior 23%, the exterior 11% and the electrical & other equipment about 14%.



Source: Mazumdar 2013, with adaptations on the use of aluminium

Figure 2: Weight distribution of car components and materials used for their construction

Figure 3 provides an overview on different materials and their share on the mass of an average vehicle (car and light duty vehicle). Steel and high-strength steel still account for more than half of the weight of an average vehicle in 2013. Aluminium and iron accounted for roughly 9% and 6%, respectively. Plastics achieved about 8%, while glass fiber composites and carbon fiber composites only reached minor shares of 1% and 0,007%, respectively. Premium cars of German manufacturers may deviate significantly from this average materials composition. For instance, Audi builds whole body-in-white of several models in Aluminium, while BMW for their electrified i3 models uses carbon fiber reinforced plastics (CFRP) for the passenger cell i.e. the upper part of the i3 body-in-white. In both cases the experience to use these materials in specific cars is transferred to other models and further components e.g. the C-pillar of the new 7-series of BMW. In such cars the share of steel on total weight will be drastically reduced and those of alternative lightweight materials increased. In summary, major options for lightweight materials are[2]:

- High strength steel (HSS)
- Aluminium (AL)
- Magnesium (MG)

[2] A few authors also mention wood as a promising lightweight material.

- Glass fiber reinforced plastics (GFRP)
- Natural fiber-reinforced plastics (NFRP)
- Carbon fiber reinforced plastics (CFRP).

Source: Mazumdar 2013

Figure 3: Weight shares of different materials of an average car[3]

A further element of lightweight construction is to develop components that are made of different materials combining e.g. different metals, metals with plastics etc. Such multi-material designs require innovations in joining technology and production processes. Therefore, research on materials characteristics, joining technology and production processes is considered the major key for unfolding the lightweight potential of metals and fiber composites (Gude et al., 2015).

The usage of the different materials for lightweight construction where the materials characteristics open up a choice between materials depends on the relationship between weight savings and cost increases. As a rule of thumb, higher weight savings also come at a higher cost. Of course, such an assessment is very dynamic as innovations and cost reductions of lightweight materials develop fast today. In 2009 experts considered lightweight materials still a relatively expensive method to reduce energy demand of vehicles (Frost & Sullivan,

[3] Obviously the numbers in Figure 3 are modelled as there exists no detailed global database on vehicle composition by material and weight. Therefore other reports with modelled values exist and comparing them leads to ranges of values for the shares of different materials on vehicle weight. For example, for the use of aluminium in cars sold in Europe other estimates indicate that in 2012 the weight share of aluminium was 10% growing to 11% in 2015 (Ducker 2016).

2009). Since then, this has changed and using lightweight materials in cars has been increased. Acceptable price tags for saving weight by lightweight materials are estimated at 7 €/kg saved for conventional cars and 18 €/kg for electric vehicles (Gude et al., 2015).

The acceptable price tags for lightweight construction of cars with combustion engines differ between vehicle segments. The highest cost premiums can be borne in luxury cars and sports cars, while for the smallest car segments the premium is (close to) zero. Table 1 provides an indication of the cost premiums for different segments and as well for different locations in the vehicles as also the weight distribution across the whole vehicle plays an important role for performance and comfort characteristics of a car.

Table 1: Acceptable additional cost of lightweight construction by car segment

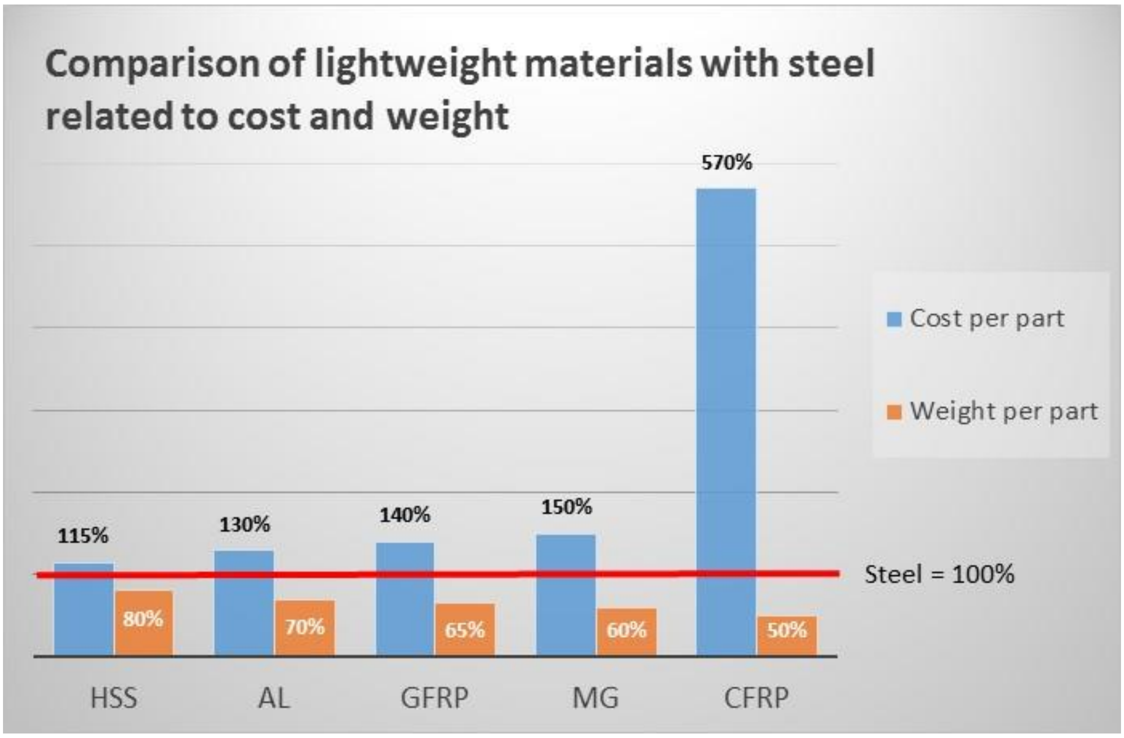
Vehicle segment	Limit of additional charges regarding a weight reduction		
in € per kg saved	front bottom	rear bottom	above centre of engine
luxury car class	2,1	3,4	7,1
superior car class	1,7	2,8	5,7
superior middle car class	1,3	2,1	4,2
middle car class	0,8	1,4	2,8
small car class	0,3	0,6	1,1
mini car class	-	0	-

Source: Eickenbusch/Krauss, 2014

The acceptable additional cost of light weighting in Table 1 differs from the values mentioned earlier. This indicates that there is a range of potential applications and valuation of benefits of saving weight.

Figure 4 provides a comparison of the weight reduction potential of lightweight materials and the cost increases in comparison to steel. It should be pointed out that these values are indicative as the exact values are strongly dependent on type and shape of the part analysed and on the materials specifications (e.g. in case of GFRP the values refer to a part produced with thermoplastic as a matrix material). The basic observation is that achievable weight reductions are lowest for HSS (-20%) and improve in this order for AL (-30%), GFRP (-35%), MG (-40%) and CFRP (-50%) with the latter roughly halving the weight of a part. The literature actually reports a range of values for the weight saving potential of different materials. While Lanxess (2013) for aluminium estimated a potential of 30% Audi is reporting for their A6 model a saving of 40% (Audi 2011). On CFRP Lanxess (2013) estimates 50% weight savings while other experts even expect savings of 60 to 70% (RMI 2013).

On the cost side the order is consistent starting with HSS causing the lowest cost increase (+15%) and then AL (+30%), GFRP (+40%), MG (+50%) and the CFRP (+470%). The high price premium of CFRP points to the requirement to reduce the cost of CFRP manufacturing in the future to make it competitive with the other lightweight materials. Given the further materials characteristics of CFRP like the 40 times higher tensile strength than steel this will be a valuable R&D effort.



Source: M-Five with values from Lanxess 2013

Figure 4: Relative mass reduction potentials and cost ranges of lightweight materials compared with steel[4]

Two limiting factors need to be considered when discussing the use of lightweight materials for reducing energy demand and greenhouse gas emissions (GHG) of cars:

- Recyclability and recycling of materials.
- Life-cycle assessment (LCA) of materials, in particular related to energy demand and GHG.

The EU directive on end-of life vehicle (Directive 2000/53/EC) transferred into German legislation by the so-called AltFahrzeugV[5] (last updated 2015) requires that from January 2015

[4] Both on cost comparison as well as on weight comparison exist a range of studies, e.g. indicating higher weight reduction potentials for aluminium (40% instead of 30% as in the figure) or lower potentials for CFRP (45% instead of 50%). Other sources like the US Institute for Advanced Composites Manufacturing Innovation (IACMI) observe cost reductions of CFRP of over 50% today.

[5] „Verordnung über die Überlassung, Rücknahme und umweltverträgliche Entsorgung von Altfahrzeugen (Altfahrzeug-Verordnung - AltfahrzeugV)“. Last updated on August 31st 2015.

onwards 95% of vehicle mass of a scrapped car need to be re-used or recycled. This includes “recycling” by means of waste-to-energy conversion. The latter can only account for 10% of vehicle mass, as the second condition of the regulation requires that at least 85% of weight is re-used or materials recycled, which excludes the waste-to-energy “recycling”. While for steel, aluminium and magnesium recycling processes are well-established this does not hold for the non-metal parts of a car, in particular for the plastics including GFRP and CFRP, such that recycling processes and uses of these materials need to be developed and implemented by the industry.

Also the use of lightweight materials causes secondary effects on increasing the pressure for recycling of existing non-metal parts of a car. The lighter a car gets through lightweight materials the larger will be the share of non-metal parts of a vehicle already implemented just because of the mathematics of a shrinking base for the percentage calculations.

The second limitation is related to the life-cycle energy demand of different materials. In terms of energy saving and GHG emissions the use of a lightweight material is beneficial when the energy saved during lifetime of a car due to less weight of a part is larger than the additional energy required to produce the part in relation to the otherwise used material e.g. steel. This aspect is relevant since lightweight materials like aluminium, magnesium or CFRP require significant energy input for their production.

High strength steel (HSS) and aluminium (AL) are the lightweight materials most often used in manufacturing of cars today (2015/2016) as under current technological and political conditions their potential of weight reduction in relation to cost and their recyclability is most suitable. Also for GFRP and NFRP a number of suitable applications in terms of cost versus weight performance exists, while recyclability may be an issue of future improvements. Magnesium (MG) seems to be inferior to the other options as despite a longer period of application cost is substantially higher than for the other metal options and the material is facing the issue of corrosion due to its chemical activity. Therefore its use today as well as for the future seems to be limited to niche applications.

In terms of weight reduction, stiffness and formability and low usage profile today the lightweight option with the potential of disruptive change would be CFRP. Three challenges will have to be solved to increase the use of CFRP in car manufacturing substantially: (1) cost (including cycle time reduction), (2) recyclability, and (3) life-cycle energy balance. Actually the three challenges or the solutions to the challenges are not independent: high cost is partially due to high energy demand for production of raw materials as well as of CFRP parts. Reducing energy demand will bring down cost and life-cycle energy balance. Recycling of carbon fibers will bring down cost as well and probably will also reduce energy demand.

As many studies have shown that the mix of materials to construct a car is becoming more multifaceted. Steel is incrementally loosing shares. Various lightweight materials are benefitting, today and in the near future in particular aluminium (Behr/Füller 2015, Ducker 2016). As our analysis revealed that CFRP would bear the potential for disruptive change that when it occurs would significantly alter future scenarios of material composition we focus in more detail on this material.

3 Carbon fiber reinforced plastics (CFRP)

Carbon fibers have the best **mechanical characteristics** among all reinforcing fibers: high stiffness and elasticity module, very low density, high fatigue strength and high temperature-resistance. Furthermore, their elementary composition allows to completely reduce the thermic extension in at least one direction. However, damages are barely recognizable as the material is nontransparent. Carbon fibers conduct electricity (Grillitsch, 2013).

Therefore, carbon fibers are very popular in lightweight construction in spite of the difficult production processes they require. The material is employed for components that need to be particularly light and stiff, such as in aviation, prosthesis, automotive and engineering industries. Carbon fiber reinforced plastics (CFRP) represent half of the weight of the Boeing 787 and Airbus A 350, and rotor blades of wind power stations are made of carbon (Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA, 2014). It should be pointed out that these industries produce small series products for which CFRP components can be produced in a manufactory style or even are handmade while for the automotive industry, apart from super luxury cars, the CFRP components will need to be produced in an automated style to achieve high production volumes at moderate cost.

Different industries make use of different types of rovings. Aerospace industry is applying so-called *small-tow* fibers, in which a roving contains 24,000 (24K) or fewer filaments. The automotive industry is working with *large-tow* fibers (sometimes also called heavy tow) where a roving may contain on the order of 48,000 to 320,000 (48K – 320K) filaments or more. A representative value seems to be 50k filaments. This means, our analysis of the value chain and production capacities needs to focus on the large-tow fibers.

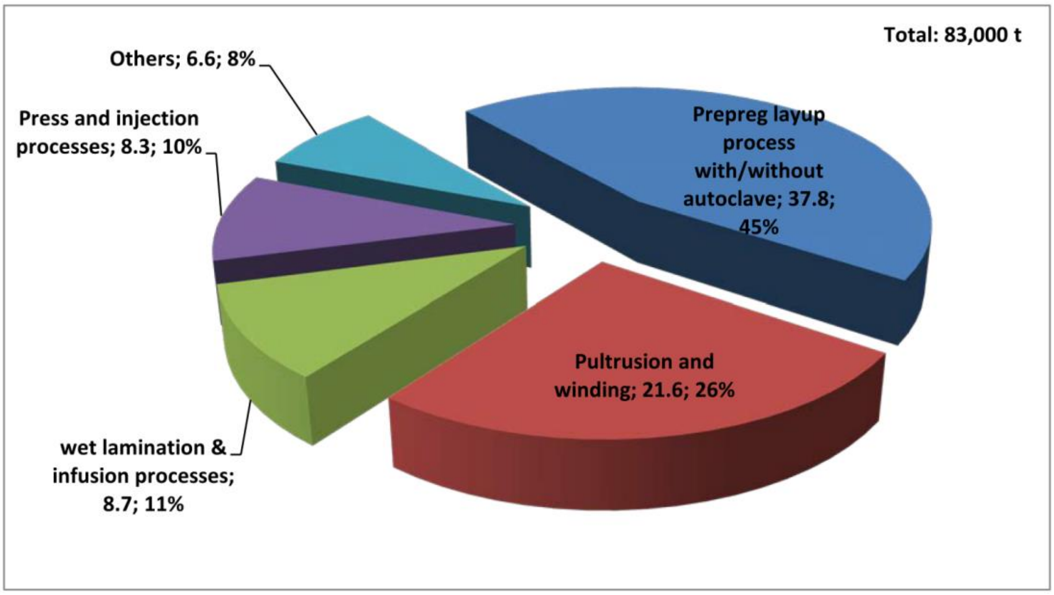
3.1 Technology and production of CFRP

Basically, the production process of CFRP can be split into four major steps, as for other parts, which are (1) preparation of raw materials, (2) production of semi-finished parts, (3) parts production, and (4) finishing of part. Each of these steps of CFRP production for automotive use bears high potentials for improvements of the production process and for reductions of costs.

Raw materials of CFRP constitute the carbon fibers and their precursors. Currently, more than 95% of **carbon fibers** for high performance CFRP materials are made of the petroleum based polymer polyacrylonitrile (PAN). The production of carbon fibers takes place in several steps during which the PAN fibers are first stabilized at temperatures of about 300 ° C before passing the carbonization oven at temperatures of 1.300 degrees and finally undergoing a heat treatment under Argon atmosphere at 1.200 to 3.000 degrees. The higher the final treatment temperature, the higher their tensile strength and the tensile modules of the final carbon fibers. This process chain as well as the prior production of PAN fibers require high energy input and are thus costly. To bring energy demand and cost of this process down is the focus of research. On the other hand, the use of alternative precursor materials could significantly reduce costs, energy and resource needs. For instance, the production of carbon fibers on the basis of mesphase pitch represents a possible alternative to PAN. Yet, only a small share of the current production is based on pitch precursors (Eickenbusch and Krauss, 2014).

In the medium run, **renewable raw materials** represent a particularly interesting alternative to replace petroleum based precursors. For example, the biopolymer lignin a residue of the production of cellulose has similar characteristics, but the purity and mechanical qualities are not yet meeting the requirements of the industrial production of CFRP. Therefore, the development of suitable processes for the carbon fiber production on the basis of lignin is subject of current research in Germany, for example in the project *MAIgreen* of the leading edge cluster *MAI Carbon*[6] (Eickenbusch and Krauss, 2014).

CFRP can be manufactured by different production processes that can be grouped into four major categories and a number of other less developed or less important processes. The following Figure 5 illustrates the deployment of production processes of CFRP in 1,000 tons in 2014 (Kraus et al., 2015). *Prepreg layup process* and *press and injection process* gained in importance compared with the previous year, while *pultrusion and winding* lost market share. *Wet lamination & infusion process* was stable. The reason for the gain of importance of *Prepreg layup process* largely was caused by civil aviation shifting from pultrusion and winding processes to prepreg layups. The increased use of *press and injection process* was due to the automotive industry that further scaled-up the use of the so-called resin transfer molding process (RTM) that belongs to this category of production processes. In particular the ramp-up of production of the BMW i-series cars caused this increase.

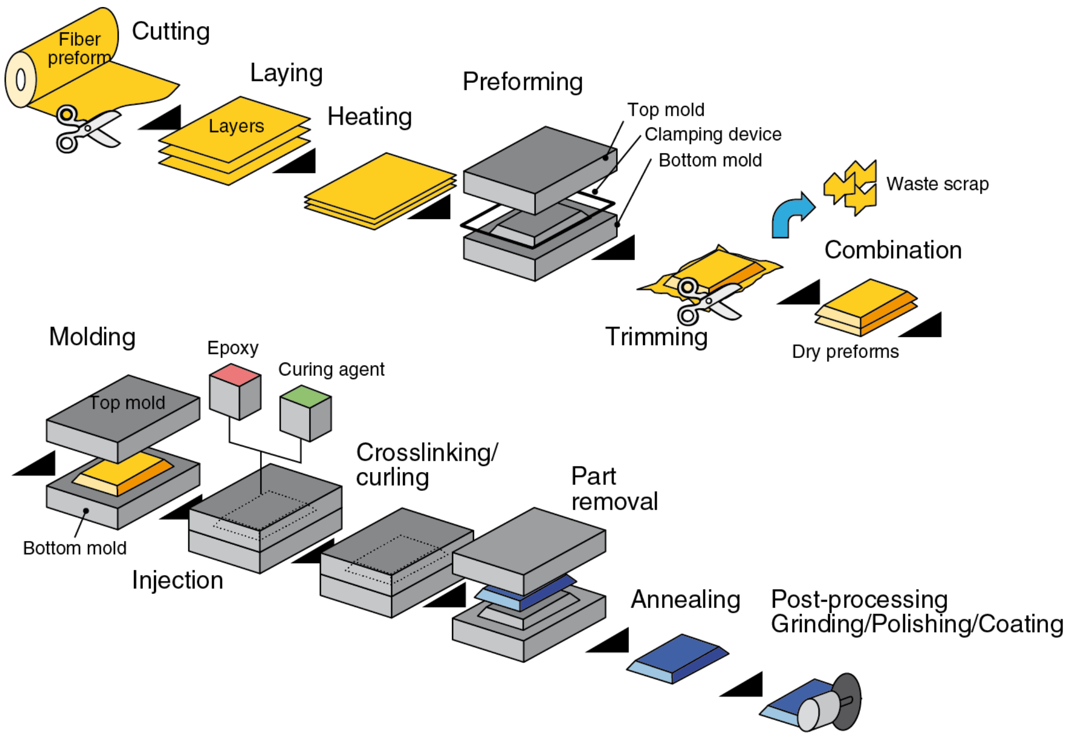


Source: Kraus 2015

Figure 5: Deployment of production processes of CFRP in 1,000 tons (2014)

[6] http://www.mai-carbon.de/index.php/de/cluster-organisation/projekte/mai-green

Different variants of the resin injection process are particularly promising for a broader introduction of CFRP in automotive construction. The most important process for the serial production of CFRP components actually seems to be the resin transfer molding process (**RTM)** (see also Figure 6): endless fibers are arranged in multiple layers, then heated in the preform process and shaped into the final component's geometry. Complex structures can be assembled of multiple such preform blanks. Afterwards, the preform blanks are put into the form adjusted cavity of the RTM press, in which the resin is then injected together with further reaction components. The reaction mix penetrates the mesh and hardens as a matrix. In order to accelerate this process and to avoid bubbles, the resin can be injected under pressure and the RTM press can be evacuated. Finally, the component can be shaped into its final form by cutting or applying openings (Eickenbusch and Krauss, 2014).

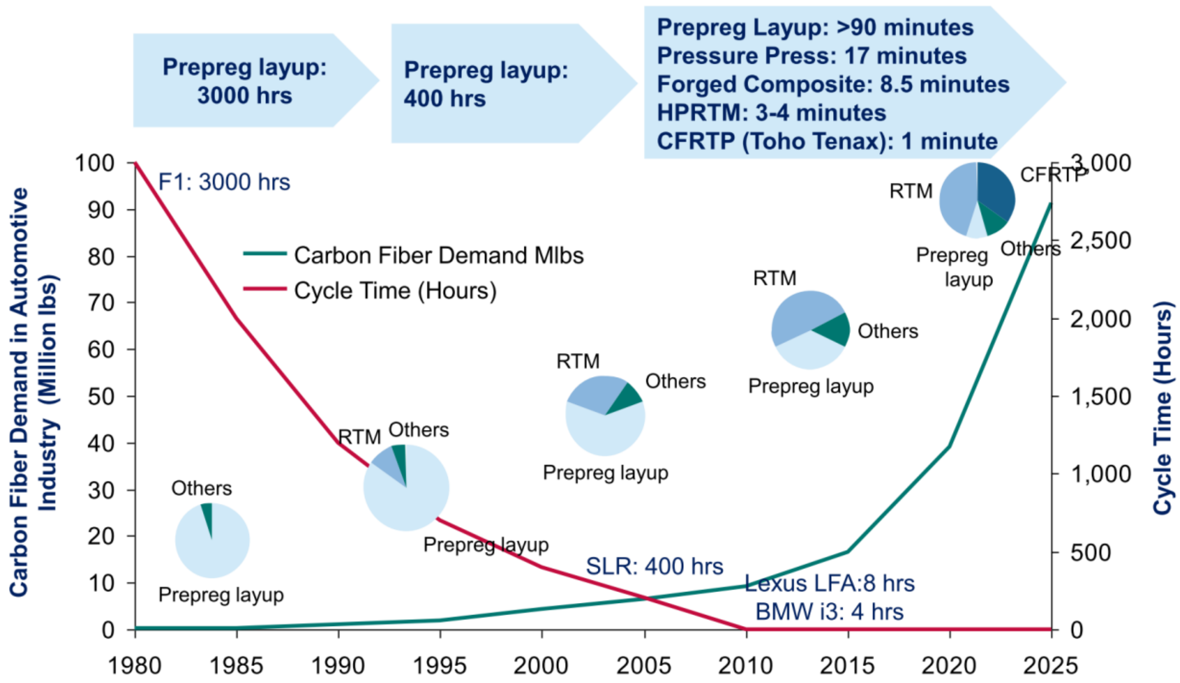


Source: Leichtbau BW 2015

Figure 6: Major production steps of the RTM process

In function of the hardening behavior of the matrix material and of the degree of automation of the process chain, the described RTM process can take 5 to 60 minutes. For automotive applications in mass series production of cars such cycle times are too long or at least a serious obstacle to produce cost competitive CFRP parts. Therefore one of the major research and innovation fields (R&O) is to speed up the hardening, curing and cooling process to reduce cycle times and cost of CFRP production.

Nevertheless, since the first automotive use of CFRP in a Formula 1 McLaren race car in the 1980ies cycle time has reduced drastically and when reaching the level of measuring in minutes instead of many hours around 2010 demand for automotive use is increasing (see Figure 7). The following figure illustrates how much the cycle time of prepreg layup has gone down and how this had led to a significant increase in the carbon fiber demand in the automotive industry. The last five years mark the switch from manual preparation of prepreg layup to automated preparation of these semi-finished parts of CFRP production (Mazumdar, 2013).



Source: Mazumdar 2013

Figure 7: Development and forecast of automotive demand of carbon fiber in dependency of the cycle time of production

In 2014 the German association of engineers (VDI) published a study summarizing the weaknesses and the R&I requirements of the German industry to develop and deploy further lightweight materials for renewable energy and efficient mobility including an analysis of CFRP (Eickenbusch and Krauss, 2014). They conclude that the development and realization of **serial production processes** for CFRP would enable the decisive breakthrough of this material in automotive production: slim production, high frequencies, short value creation chains, avoidance of intermediate materials and reliable supplies. Additionally the preconditions for the employment of fiber composite ready construction designs (highly integrated component groups such as monocoque, utilization of anisotropy) have to be laid. Fiber composite ready construction principles require the refinement of **numeric design tools enabling a better utilization of the anisotropic mechanic properties of fiber composites** and thereby the renunciation of the simple transfer of metallic design principles to CFRP. Besides the production processes, **methods for non-destructive testing** of the materials need to be developed in order to enable a fast and reliable quality control in the production and during usage.

A further challenge is **brittle failure of CFRP** e.g. under impulsive stress such as impacts or crashes. Whereas metals deform plastically, CFRP construction transform the impulse energy via fragmentation. For the development of crash and impact tolerant structures, FE-/ particle methods need to be refined and new, ductile duromer resin systems need to be developed.

Damaged components need to be reparable. Therefore, economic processes suitable for anisotropic construction principles need to be developed. Weldable and deformable fiber-reinforced materials with thermoplastic matrixes offer a high potential for new lightweight constructions which was not yet exploited because of the materials price and unsatisfactory availability. Their capacity of chemic joining with e.g. metals therefore make them an ideal material for metal-CFRP hybrid materials. Finally, the afterlife of these materials needs to be clarified.

The growing signification of multi material systems and hybrid constructions **requires new joining technics** such as mechanic joining, hybrid processes and especially gluing. In order to reach lightweight objectives, material innovations in the field of functional integration offer decisive contributions. In fields of application with low unit lots, generative production processes such as laser sintering are advancing (3D printing). In how far such processes can be employed in large series production remains unclear (Eickenbusch and Krauss, 2014).

Concerning **matrix materials**, duroplastic and especially epoxide resins dominate the market with a share of about 90%, while CFRP with a thermoplastic matrix will gain importance in the future (Eickenbusch and Krauss, 2014).

In summary, there are a number of major technology and production issues still to be solved to achieve mass-market application of CFRP in automotive use:

- Development of a cheap precursor to carbon fibers.[7]
- Reduction of energy demand of carbon fiber production.
- Development of reliable modeling and simulation tools for computer-aided design of CFRP.
- Development of non-destructive testing methods for CFRP.
- Reduction of cycle times of CFRP production, in particular for the RTM process.
- Recycling to comply with the recycling regulation and to reduce cost.

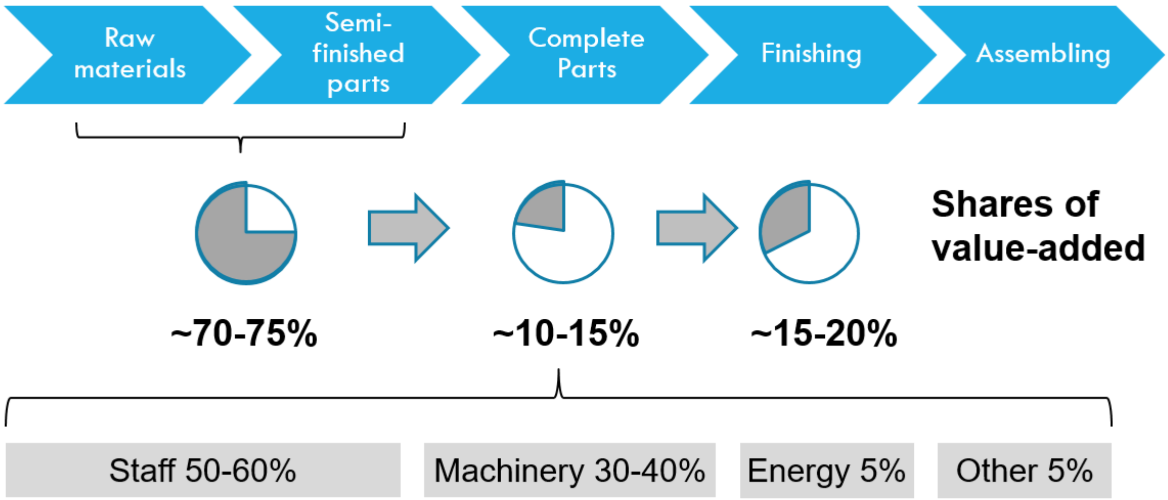
3.2 Value chain of CFRP

There is not **one** value chain of CFRP. The value distribution depends on the purpose and structure of the part to be produced, the production process chosen and the regional structure of the locations of the value chain. Therefore the following paragraphs use examples of

[7] In 2016 the Oak Ridge National Laboratory (ORNL) offered their new process to produce carbon fibres from acrylic fibre at 50% cost and with 60% less energy demand compared with conventional PAN technology to US companies for licensing (press release from March 22nd 2016).

relevant production processes for automotive CFRP and of value chains to explain the logic of CFRP value distribution.

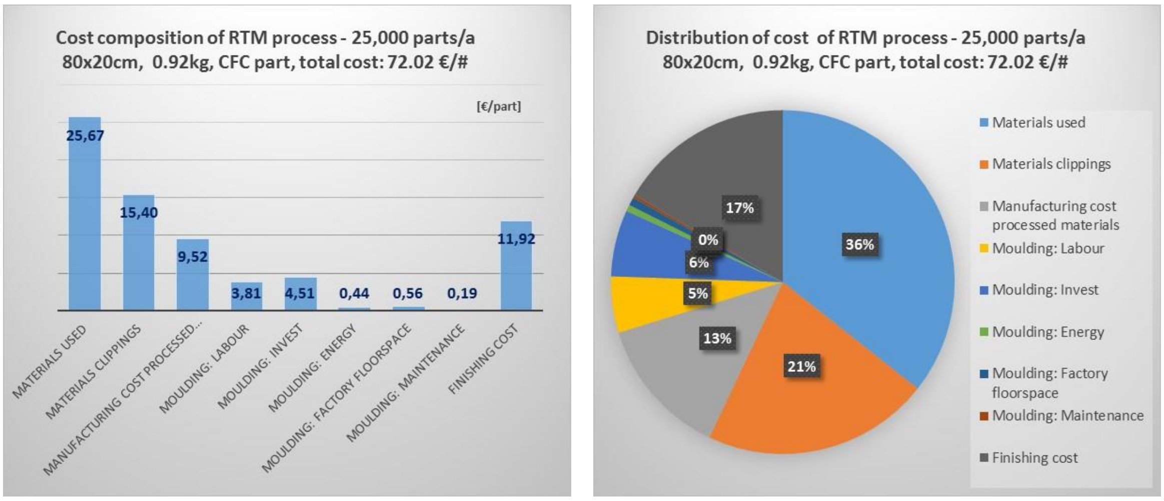
As one example we use a German study commissioned by the Development Agency for Lightweighting of Baden-Wuerttemberg. In the study models for the analysis of costs structures and value creation shares of different lightweight options including CFRP were developed (Leichtbau BW GmbH and Fraunhofer-Institut für System- und Innovations-forschung ISI, 2014). Calculations were made for the RTM process (see Figure 6 above for the technology steps) and for the Sheet Molding Compound process (SMC) for different types of parts. The following Figure 8 illustrates the value chain of the resin transfer molding process (RTM). Manufacturing of the raw material (i.e. the carbon fibers) plus manufacturing of the semi-finished products (i.e. the fabrics or prepregs) accounts for about 70 to 75% of value of producing a CFRP for automotive use by the RTM process. The production of the part by the RTM process is generating about 10 to 15% of value and the finishing of the part about 15 to 20%. Obviously this analysis shows the high value share of carbon fibers and fabrics or prepregs on the value chain of CFRP. A second indication is the substantial share of labor cost on the step of parts production. It should be noted that the analysis refers to the state-of-art of 2014 and is subject to a fast development of innovations as we will point out by the US analysis explained later on.



Source: M-Five based on Leichtbau BW 2015

Figure 8: Value chain of CFRP components produced by resin transfer molding process (RTM)

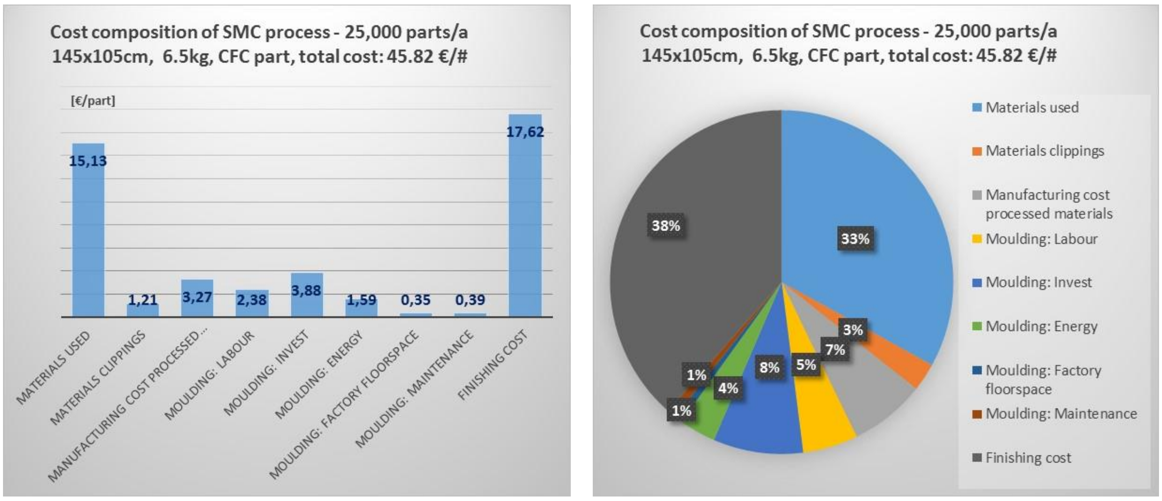
The following Figure 9 illustrate the results of the costs analysis of the **RTM process** of an exemplary component of a lot size of 25.000 units per year and with a weight of close to one 1 kg. The cost share of materials and producing the semi-finished parts account for 70% (36%+21%+13%). It should be highlighted that clippings of materials account for 21% of the total cost, which points to two issues: (1) the high potential to reduce cost by avoiding clippings, and (2) the significant quantity of carbon fibers that could be recycled from the clippings. The whole production of the part by the RTM process accounts for 13% and the finishing of the CFRP for 17%.



Source: M-Five based on Leichtbau BW (2015)

Figure 9: Cost estimate of the value chain of the RTM process - 2014

The analysis of unit cost of a part of 6.5 kg weight in function of the material costs, component complexity and hardening time of the **SMC process** in 2014 made evident that component costs in the SMC process are less sensitive to material costs than RTM (see Figure 10). Only 43% of the value of a CFRP produced by SMC process accounts for materials and semi-finished parts. The clippings amount to 3%, only, compared with the 21% of the RTM process. The SMC process itself accounts for 19% of value, while finishing is significantly more costly with SMC (38%) than with RTM (17%) (Leichtbau BW GmbH and Fraunhofer-Institut für System- und Innovationsforschung ISI, 2014).



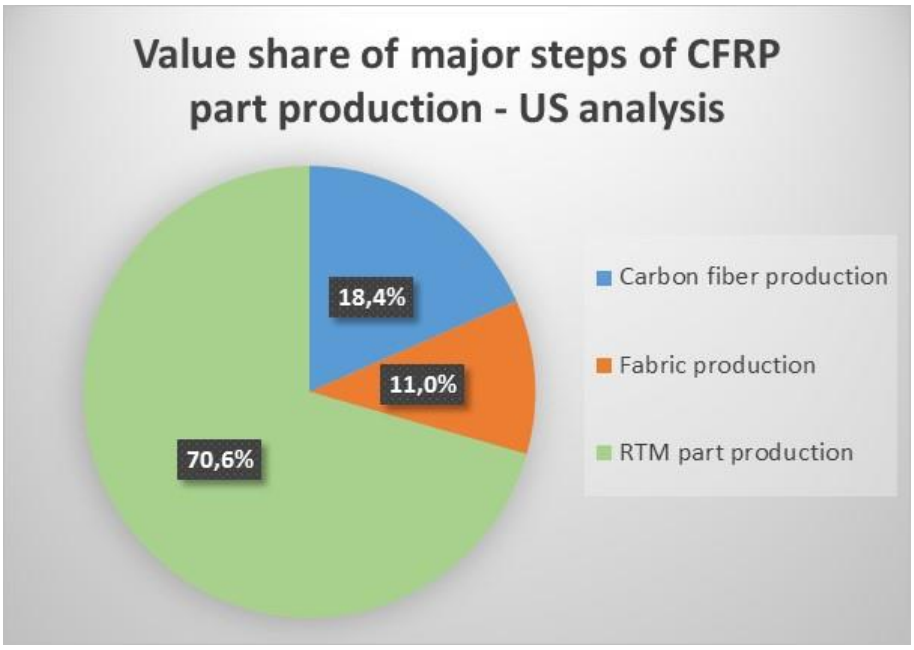
Source: M-Five based on Leichtbau BW (2015)

Figure 10: Cost estimates of the value chain of the SMC process - 2014

The part cost per kg of the two parts differs significantly: the RTM part comes at a cost of about 78 €/kg, while the SMC part costs about 7 €/kg of part weight.

A number of sensitivity analyses were carried out as well. For RTM there was a high cost degression observed until annual production of 10,000 parts; for SMC this was the case until about 50,000 parts per year. The second strongest impact on cost after the lot size were the materials cost. The time of hardening as another crucial factor was more relevant for the SMC process than for RTM process. (Leichtbau BW GmbH and Fraunhofer-Institut für System- und Innovationsforschung ISI, 2014).

For the US the Clean Energy Manufacturing Analysis Center (CEMAC) undertook a global competitiveness analysis of the carbon fiber composites supply chain (CEMAC 2016). They analysed five potential supply chains, two based on existing chains in the automotive industry and three hypothetical chains, of which one was to locate the whole chain in Germany. The supply chain analysis was based on the production of an upper dash panel using bidirectional fabric made of carbon fibers and weighing about 1.8 kg. The supply chain was split into three major steps (1) carbon fiber production, (2) fabric production, and (3) part production using the RTM process, which can be compared with the steps as considered in our RTM value chain presented in Figure 6 based on the German analysis of Leichtbau BW. However, as Figure 11 reveals the value shares of the three steps substantially differ. Carbon fiber production accounts for about 18% and fabric production for about 11% such that the whole production of the semi-finished part, i.e. the fabric, accounts for roughly 30% compared with the 70% allotted to these steps in the German analysis shown before.



Source: M-Five with data from CEMAC 2016

Figure 11: Value chain for CFRP part production – all steps undertaken in US

Table 2 provides an overview on the cost of the different value chain structures based on 2015/2016 data, which is more recent than for the data of the German analysis in Figure 8 to Figure 10. The first chain UGG builds on the BMW i3 chain (see also section 3.3) starting with carbon fiber production in the US (using precursor produced in Japan) followed by fabric production and part production both in Germany. Shipping cost between different locations have been included. The second chain UUU builds on existing chains of CFRP production for US luxury sports cars for which all three value steps including the precursor production are located in the US. The three other chains analyse the cost potential of modifications of the existing CFRP value chains. GGG and JGG would shift the carbon fiber production of a BMW i3 type value chain from the US either to Germany (GGG), as the country where the further production steps take place, or to Japan (JGG) as the country in which market leaders of precursor and fiber production are located. However both chains suffer due to high electricity cost in these countries, which account for a share of 11% of value of carbon fiber production in the US, while in Germany and Japan this share would roughly double increasing the cost per kg of carbon fiber by about 2 US$ (CEMAC 2016).

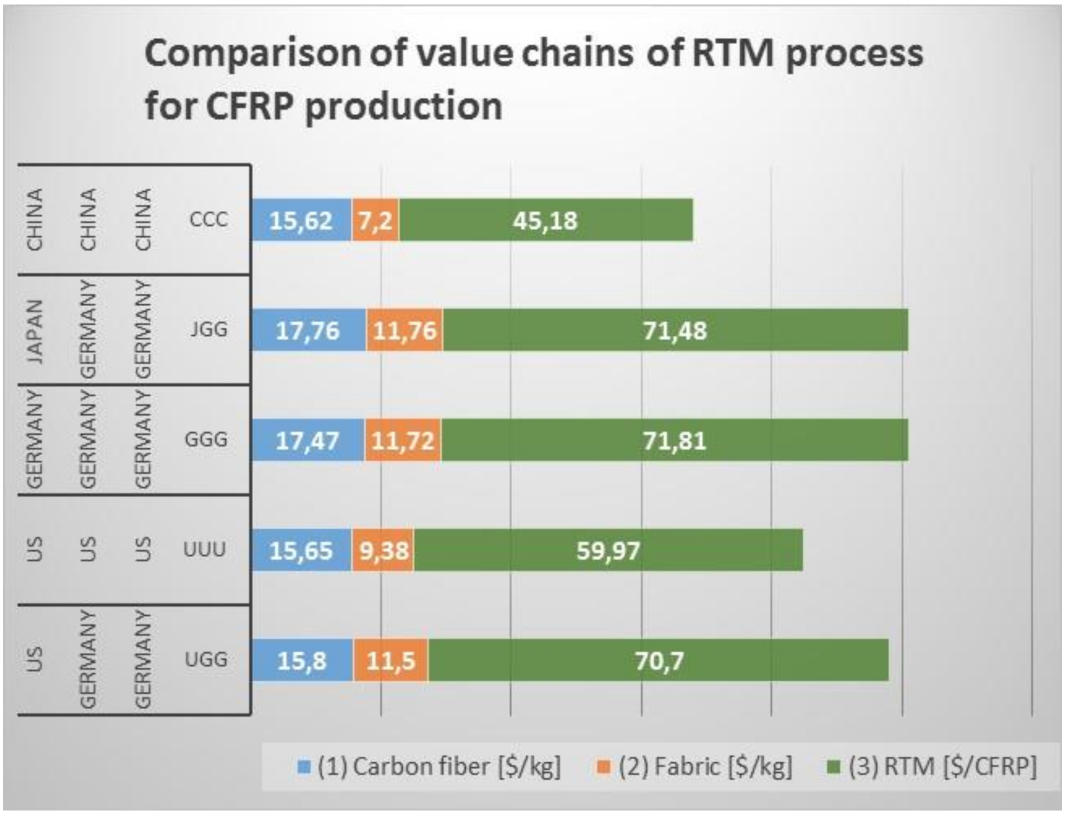
Table 2: Cost after major elements of value chain of CFRP production

(1) Carbon fiber	(2) Fabric	(3) RTM part	Chain structure	(1) Carbon fiber	(2) Fabric	(3) RTM
Location of value step			Acronym	$/kg	$/kg	$/CFRP
US	Germany	Germany	UGG	15,80	27,30	98,00
US	US	US	UUU	15,65	25,03	85,00
Germany	Germany	Germany	GGG	17,47	29,19	101,00
Japan	Germany	Germany	JGG	17,76	29,52	101,00
China	China	China	CCC	15,62	22,82	68,00

Source: M-Five after CEMAC 2016

Figure 12 provides an overview of the cost of each step of the five value chains. Consistently for all chains the final step, the part production, accounts for the highest value share. In the Chinese based value chain (CCC) this share is two third, while it is substantially higher in the other chains. The major reason for the lower total cost as well as the lower cost of step 3 are the low labor cost in China. In the US value chain the labor cost account for about one quarter of the value of the final step, 14% of the second step and 7% of the first step. In China the labor cost are assumed a fraction of these shares.

In summary the regional differences of cost of the value chains are mainly dependent on the labor cost and the electricity prices.



Source: M-Five with data from CEMAC 2016

Figure 12: Comparison of value chain for CFRP part production

The CEMAC team also undertook a sensitivity analysis of each of the three steps of the value chain to identify the most relevant parameters. For both the first and the second step the cost of the raw materials, i.e. precursor (1st step) and carbon fiber (2nd step), and the electricity price were found to be the most sensitive influences on the cost of these steps of the value chain. For the part production applying RTM (3rd step) it was found that the molding cycle time was the most important parameter again followed by the raw material price, i.e. the cost of the fabric. This result is consistent with our previous findings that the factors determining the value chain most are:

- The cost of raw materials i.e. precursor.
- The cost of electricity and/or the energy demand to come from precursor to carbon fibers.
- The cycle time of the part production process, in particular of the RTM process.

Further we have identified the share of clippings as another important factor affecting the value chain of CFRP.

We could also identify expectations and signals that future cost of CFRP could shrink substantially. Manufacturers of carbon composites expect a 50% cost reduction of carbon fibers and an 80% cost reduction of production processes (fabric and RTM) over the next years to come (Herbeck 2014).

As one of the elements of the US Recovery Act after the financial and economic crisis of 2008 the Carbon Fiber Technology Facility was established at ORNL. This lab offers testing facilities to US automotive and supplier companies and has recently announced to have identified a process to produce carbon fibers at 50% less cost and at 60% less energy then required by the conventional fiber production using PAN (Polyacrylonitrile). This process is based on Acrylic Fibers used in the textile applications. The laboratory is offering US companies to apply for licenses for the invented carbon fiber production process that was filed for patent under U.S. Patent Application 62/273,559, filed December 31, 2015[8].

Earlier studies dated from 2012 expected a cost reduction of CFRP until 2020 of 30%, of which a cost reduction of carbon fibers by 20% would contribute to (Lässig et al. 2012). That means, today within shorter time periods (2014 to 2020) higher reductions are assumed to be feasible, which documents the technical progress that has been achieved in relation to CFRP manufacturing for automotive use over the last one or two years.

3.3 Case study: BMW's CFRP value chain

The US colleagues from CEMAC and ORNL have also pointed out that the joint venture of BMW with SGL Automotive Carbon Fibers (ACF) is most advanced in establishing an affordable and reliable production chain for CFRP at industrial scale. An assessment that will

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[8] Link to the licensing opportunity: https://www.fbo.gov/index?s=opportunity&mode=form&id=8d64c7f283bf456731ea8be211861ddd&tab=core&_cview=0.

be shared by most industry analyst. There is substantial literature in Germany and the English speaking automotive community on CFRP production. However, our understanding is that most of the literature resulting from 2014/2015 or earlier is to some extent outdated with respect to cost estimates along the value chain and industrial innovation has pushed the application frontier already further than expected by analysts in those years. Therefore in the following we present a textbox that was provided to us by BMW to explain their process and their achievements in the manufacturing and use of CFRP in automobiles. We would like to thank BMW for their permission to use the text. The structure of the value chain is illustrated in Figure 13.

Source: CEMAC 2016

Figure 13: SGL-BMW value chain of CFRP production

BOX: the BMW achievements for CFRP production

The Life module – the passenger cell of the future BMW i3 – is made primarily of carbon fibre-reinforced plastic, i.e. CFRP. The use of this light and crash-resistant high-tech material on such a scale is unique in the mass production of a vehicle, as the large-scale use of CFRP was previously deemed too expensive, and the processing and manufacture too complex and insufficiently flexible. But BMW Group recognized the potential of the material early on, and after over ten years of intensive research and process optimization, materials, systems and tools, the BMW Group is the only automobile manufacturer to possess the necessary expertise for industrialized CFRP mass production. The advanced level of the production process today is discernible above all in the process safety achieved, the fast cycle times, and the high standard of quality in the CFRP components produced.

Together with the affiliated joint venture SGL Automotive Carbon Fibers (ACF), the BMW Group holds a unique position in the industry as the “owner” of all process steps, from fiber production through to the recycling of fibers and composites.

Moses Lake: carbon fiber manufacture with hydroelectric power.

A precursor, a thermoplastic textile fiber made of polyacrylonitrile, is used to create the carbon fiber at SGL ACF in Moses Lake, U.S.A. All elements of the fiber are split off in gaseous form in a complex, multi-stage process until only one fiber is left consisting of virtually pure carbon with a stable graphite structure. This is only seven micrometers (0.007 millimeters) thick, compared to a human hair, which measures around 50 micrometers. For use in the automotive sector, around 50,000 of these individual filaments are combined into “rovings” or “heavy tows” and wound for further processing. In addition to the automotive applications, fiber composites of this thickness are also used in large turbine blades of wind power systems, for example.

To manufacture the carbon fibers in Moses Lake, all of the energy for production is obtained renewably from locally available hydroelectric power, making it 100 per cent CO2-free.

In comparison to conventional CFRP production, the CO2e (global warming potential) saving is around 50 per cent.

Wackersdorf: processing into textile fabrics.

At the second site of the joint venture, in Wackersdorf Innovation Park, the fiber bundles are further processed into light textile fabrics on an industrial scale. Unlike woven fabrics, the fibers are arranged side by side on one level rather than interlaced or interwoven with each other. A woven structure would bend the fibers and reduce the excellent properties somewhat, because it is the fiber alignment itself in the fabric that guarantees the optimal characteristics of the eventually produced component. Today several thousand tons of carbon fiber fabrics can be manufactured per year.

Landshut and Leipzig, Germany: further processing into CFRP components

The carbon fiber fabrics are further processed into CFRP body parts at the pressing plants in Landshut and Leipzig. These plants are equipped with state-of-the-art technology for CFRP in automotive manufacture. The formulation, i.e. the composition, strength and geometry of the CFRP parts, can be individually modified or adapted in the pressing plant at any time during the manufacturing process depending on the design specifications

The tailor-made carbon fiber fabric is first formed into its eventual shape in the preforming process. A heating tool gives the laminate a stable, three-dimensional form. Several of these preformed workpieces can then be assembled into a larger component.

This makes it possible to manufacture large body components, which are difficult to produce in aluminum or sheet steel. After finishing and preforming, the next process step is resonation under high pressure using the RTM process (Resin Transfer Moulding). The RTM resin injection procedure used in the aerospace industry and in boat and wind turbine construction involves injecting liquid resin into preformed workpieces under high pressure. The bonding of the fibres with the resin and the subsequent hardening lends the material its stiffness and thereby its excellent properties.

Revolution in car body construction with new precision tools

The newly produced CFRP composite components are assembled in the new car body construction hall.

Around 150 parts, one third fewer than in the conventional sheet steel construction, make up the basic form of the Life module of a BMW i3. There is no noise pollution from screwing or riveting, no sparks flying during welding, and only the latest adhesive technology is used, which is 100 per cent automated. A technology mastered by BMW alone. In the unique joining process developed by BMW, the individual components are assembled without touching to an adhesive gap of 1.5 millimeters in order to ensure optimal strength after the adhesive procedure. In the newly developed manufacturing process, all connecting components in the Life module are always separated by the same gap and so receive the same amount of adhesive. Only this precision guarantees perfect power transmission between the individual CFRP components and therefore the highest standard of quality in the mass production series. In total, there is a precisely defined bonded range per car of 160 meters in length and 20 millimeters in width.

CFRP recycling and the BMW i: a closed loop.

In different procedures, the valuable recyclable materials from production and even from damaged/scrapped vehicles are reused in automotive construction and channeled back to the production process or used in other applications.

In the recycling process, carbon fiber recycling with “dry”, unresinated material is differentiated from composite material recycling (CFRP), in which “wet”, resinated plastics are used. The dry carbon offcuts created during production can be reprocessed into valuable non-woven textiles and reused in the manufacturing cycle. Around ten per cent of the carbon fiber used in the BMW i3 now is recycled material, a process unique in the automotive industry worldwide.

In composite material recycling – the processing of resinated carbon fibers – CFRP is first separated industrially from the mixture with other plastics and, for example, processed in a pyrolysis facility. The heat from the resin breakdown process is used to separate the undamaged carbon fibers. These fibers can then be used to manufacture components and reduce the new fiber requirement. For example, the rear seat pan is made from this recycled carbon fiber. It meets the BMW quality standard 100 per cent and weights 30 per cent less than the conventional glass fiber matt construction. Ground or cut into short fibers, the recycled CFRP or carbon fibers are also used in many areas outside the automotive industry, for example, in the textile and electronics industries (housing material for control units). The use of “secondary CFRP fibers” is part of a sustainable material cycle that spares resources and secures raw materials for future uses.

The final paragraphs of the previous box provide two important remarks for the further reading of this working paper:

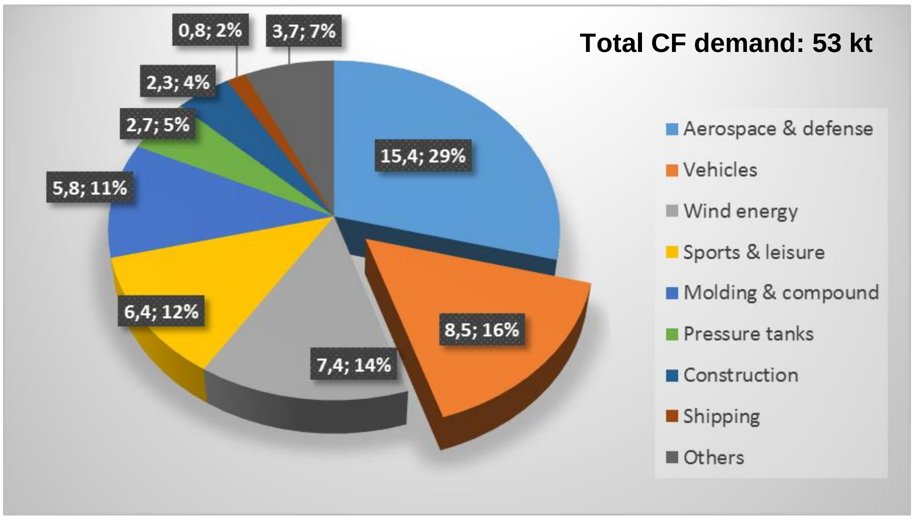
- BMW has solved the issue of recycling of the carbon fiber materials, though this involves some downcycling[9].
- CFRP is already replacing GFRP in automobiles of BMW, which is a development that seems plausible also according to our analyses.

3.4 CF and CFRP Market

Looking from the perspective of the automotive industry the market size of the global carbon fiber (CF) market would be a niche market with just close to US$ 2 Billion turnover in 2014 and a global turnover of carbon composites (CC) of US$ 16.6 Billion. However, there seems to be potential for strong and even exponential growth in the future, such that we extend this chapter on the CF and CFRP markets.

3.4.1 State of market 2014

Between 2009 and 2014 the demand for carbon fibers (CF) has been doubled from 27 kt to 53 kt. Figure 14 presents the applications in which CF have been used. In 2014 the largest demand still came from the aerospace & defense sector making-up 29% of global demand. Vehicles have already been the second largest application with 16% of the market or 8,5 kt of CF in 2014. The third largest application has been in wind energy to build the rotor blades of wind turbines. Over many years the two applications aerospace and wind energy have been most important, but vehicles have gained significantly recently.

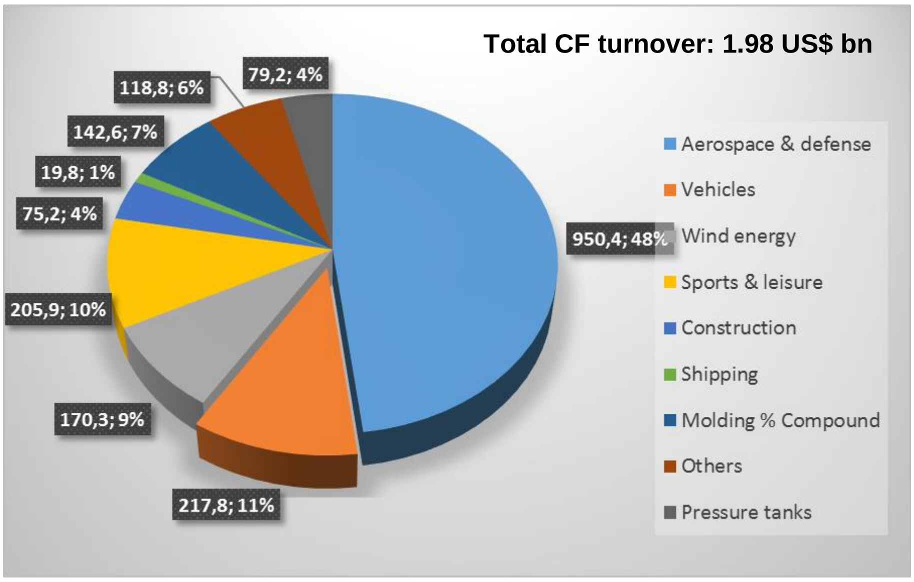


Source: M-Five illustration after Kraus et al. 2015

Figure 14: Global carbon fiber demand in 1,000 tons by application (2014)

[9] As of 2016 downcycling and pyrolysis are mentioned as the dominant recycling approach by other sources (Woidasky 2013, MAI Recycling 2015, Job et al. 2016).

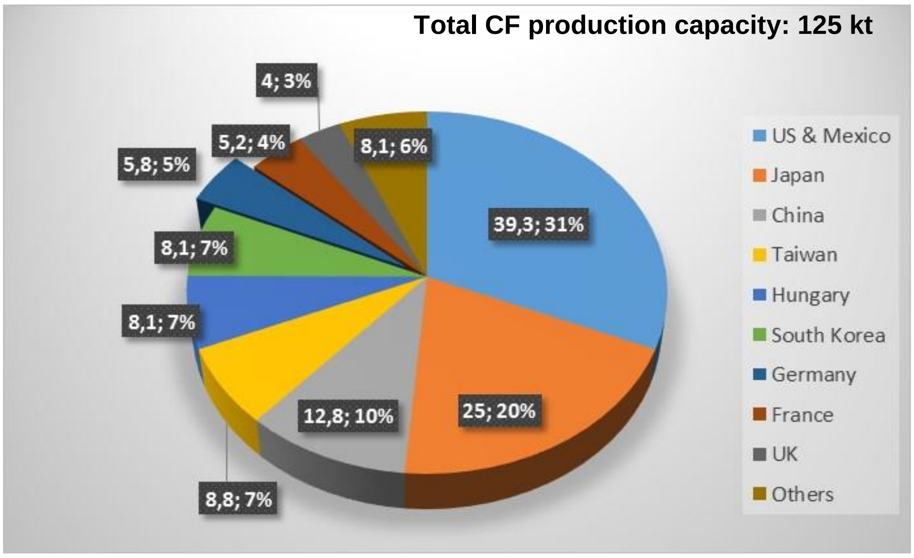
Figure 15 shows the turnover by application type. The dominance of the aerospace & defense applications is even larger as they come close to half of the market with 48% of market share. Vehicles keep their second position with 11% of market share, while in relative terms sports & leisure application gain in importance with 10% of the market. Calculating the average price of using CF in a certain application reveals that in the aerospace & defense sector 317 US$ are paid per kg CF, while in transport the virtual average would amount to 87 US$/kg, which is in the same order of magnitude as for wind turbines and sports & leisure.



Source: M-Five illustration after Kraus et al. 2015

Figure 15: Global carbon fiber turnover in US$ million by application (2014)

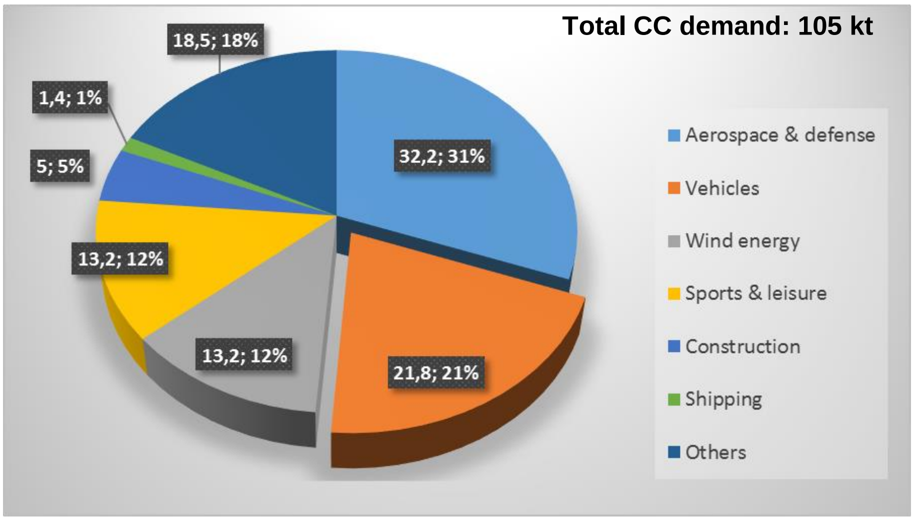
The global production capacity was more than double the global demand reaching 125 kt in 2014. Thus the CF sector suffered from overcapacity. However, this conclusion suggests a further analysis as the CF production should be segmented into the different segments i.e. small tow e.g. more used in aerospace and large tow for instance used in the automotive industry. Given the fact that additional capacity was installed in 2014 it seems that at least in the large tow segment the situation of overcapacity may not be expected for the future. Figure 16 shows that today close to one third of all capacity (small tow and large tow) is located in US & Mexico with 31%. One fifth is in Japan with 20% and only one twentieth in Germany (5%). China earlier identified as another relevant value chain actually has build up about 10% of the global production capacity in 2014 (Kraus et al. 2015). Other sources quote shares of production capacity for the year 2012 of about 45 % for Asia, and about 27% for both North-America and Europe (CEMAC 2016). This would mean that between 2012 and 2014 substantial new capacity has been built in North-America and in Asia, while Europe lost some ground.



Source: M-Five illustration after Kraus et al. 2015

Figure 16: Global carbon fiber production capacity by region (2014)

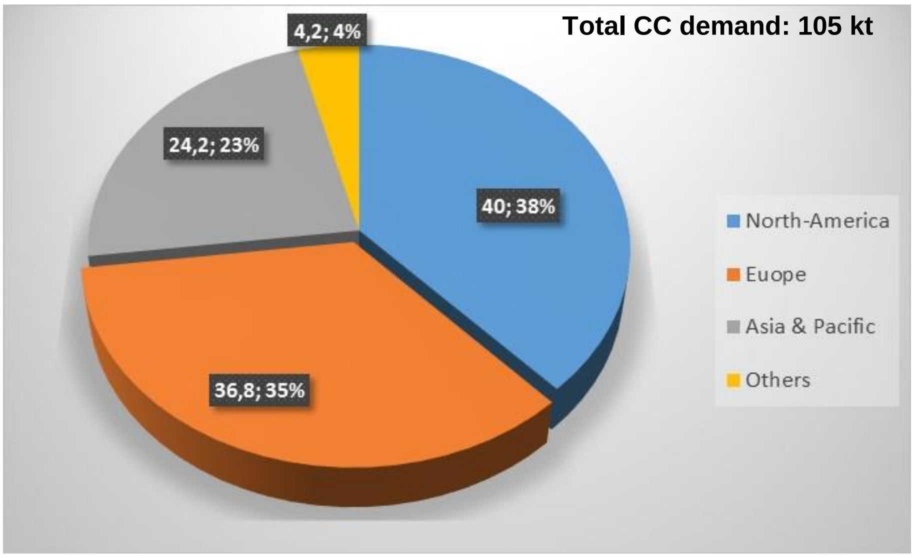
Shifting from the CF analysis to the market of carbon composites (CC) of which the CFRP accounted for 64% in 2014. Figure 17 presents the demand by applications. As with CF aerospace & defense have the highest share with 31% followed by vehicles with 21% amounting to 21.8 kt of CC in 2014. In relation to the demand of CF of 16% vehicles with 21% account for an over-proportional share of CC.



Source: M-Five illustration after Kraus et al. 2015

Figure 17: Global carbon composites demand in 1,000 tons by application (2014)

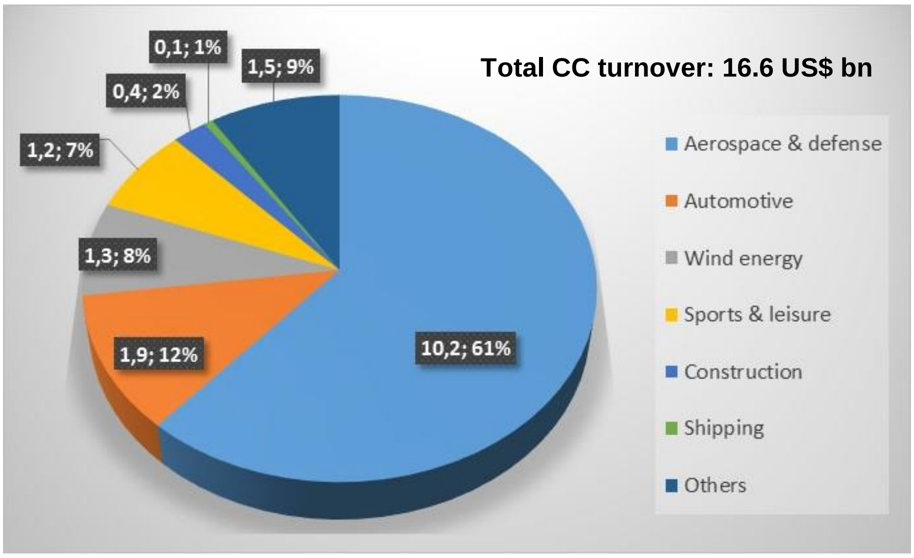
Figure 18 presents the regional distribution of demand. According to Kraus et al. (2015) the highest demand emerges from the US with 38% (40 kt). Other authors see Europe as the region with highest demand (CEMAC 2016 quoting studies for the year 2013). Nevertheless, the shares are close to each other in the range of 35% to 40% and the differences could emerge from one study looking at CC and the other at CFRP, only, which is a subgroup accounting for two third of CC. The common conclusion remains that Europe and the US are ahead of other world regions in terms of CFRP demand.



Source: M-Five illustration after Kraus et al. 2015

Figure 18: Global carbon composites demand in 1,000 tons by region (2014)

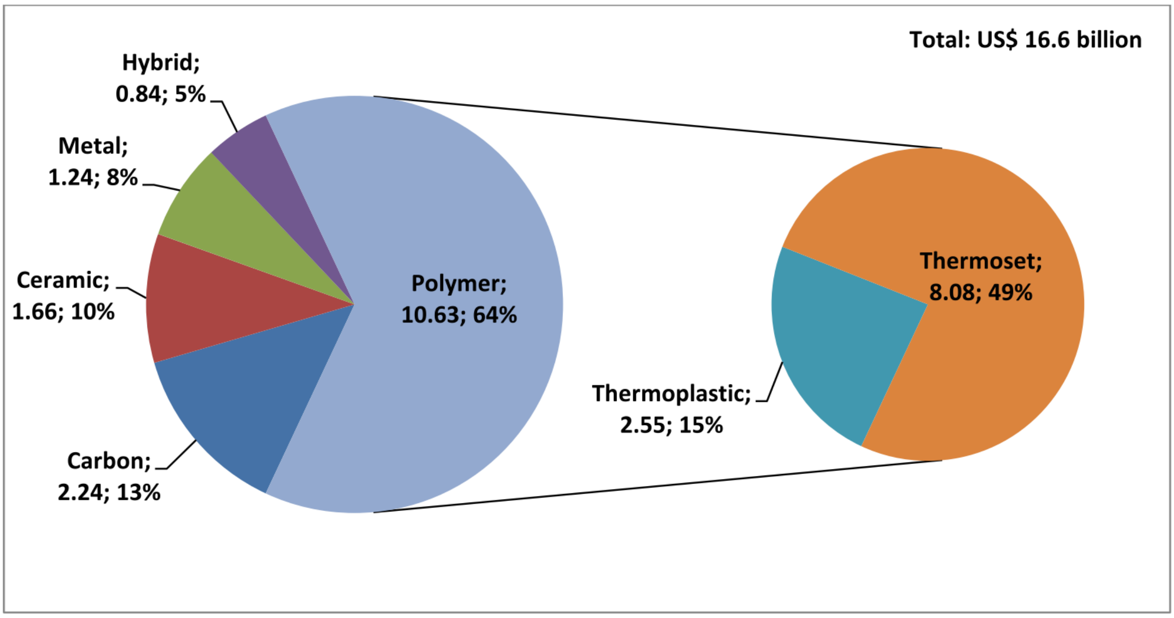
Figure 19 shows the resulting turnover by application. About 10 billion US$ or 61% of the turnover generated from CC accrues in the aerospace & defense sector, which by far generated the lion share. The second largest sector was the automotive sector with about 12% followed by wind energy with 8%. Converting the turnover into a value per weight shows that aerospace with 317 $/kg has a more than triple value per weight for their CC compared with the other sectors. The average of the other six sectors amounts to about 85 $/kg with the automotive sector being close to this average with 87 $/kg.



Source: M-Five illustration after Kraus et al. 2015

Figure 19: Global carbon composites turnover in US$ million by application (2014)

The following Figure 20 enables to extract the CFRP share on CC turnover for 2014. About 64% of turnover is generated by CFRP and out of these about one quarter is produced using thermoplastic matrix, which is more complex to manufacture but offers additional strength and infinite shelf-life compared with thermoset materials. Further it is expected that thermoplastic CFRP is simpler to recycle, though recycling technology is under development for both technologies today. Therefore we expect that thermoplastics shares on CFRP will increase in the future.



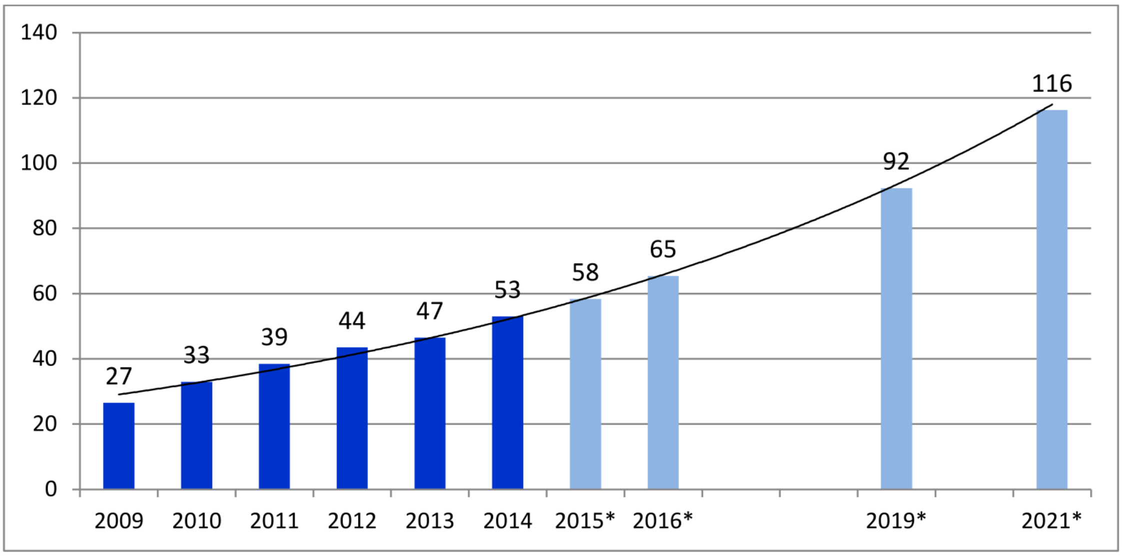
Source: Kraus et al. 2015

Figure 20: CC revenues in US$ billion by matrix material (2014)

3.4.2 Market demand forecasts

Market forecast of CF and CFRP agree that these markets will continue to grow at substantial growth rates. Compound annual growth rates (CAGR) between 6% and 20% are expected. At such rates a doubling of the market can be expected within a few years, as shown by the following Figure 21 presenting the carbon fiber demand (CF) from 2009 until 2014 as well as a forecast from 2014 until 2021. The forecast developed by the German Carbon Composites Association expects a demand of 116 kt by 2021, which is equal to a CAGR of about 12% over 7 years.

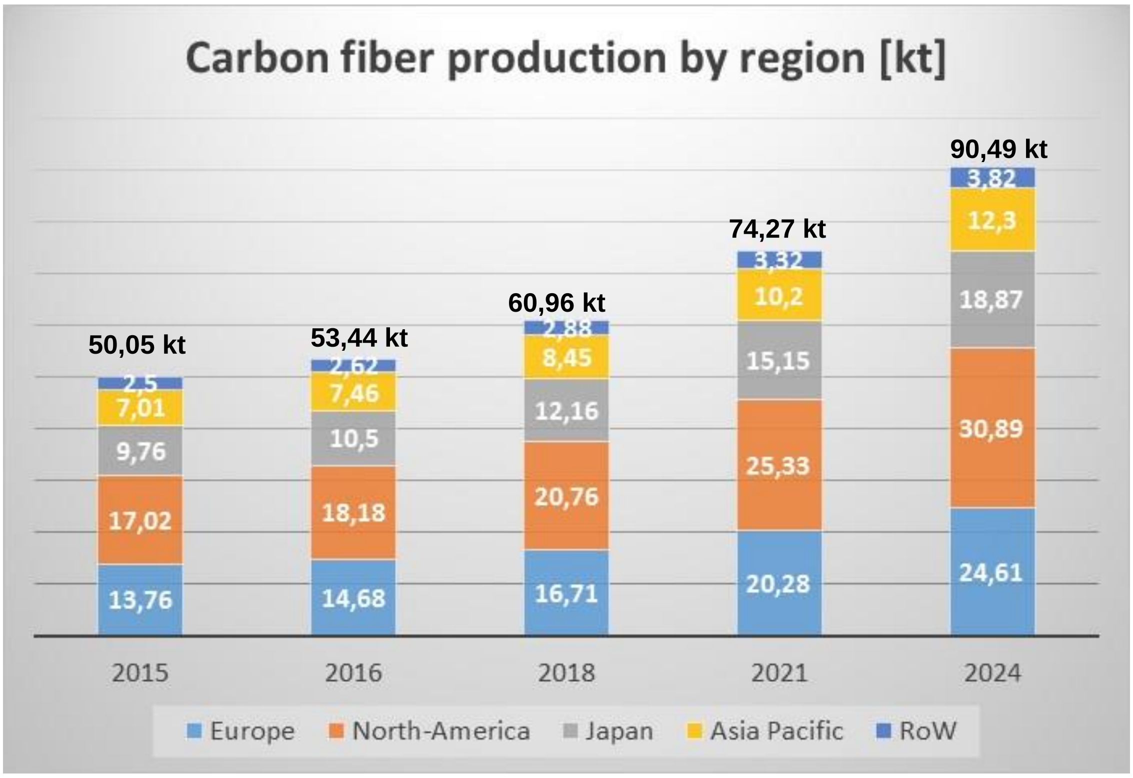
These high forecasts are not shared by all experts as shown by Figure 22, in which the total production in 2021 reaches a value of about 74 kt that is 36% lower than the German experts expect and reveals CAGRs of 6 to 7%. Nevertheless, growth of CF production according to the ACMITE experts is also taking place in Europe and remains high in Japan, which contrasts also the value chain analysis above (see section 3.2), in which it was concluded that low electricity prices would favor the US and China as locations for CF production.



** estimated values*

Source: Kraus et al. 2015

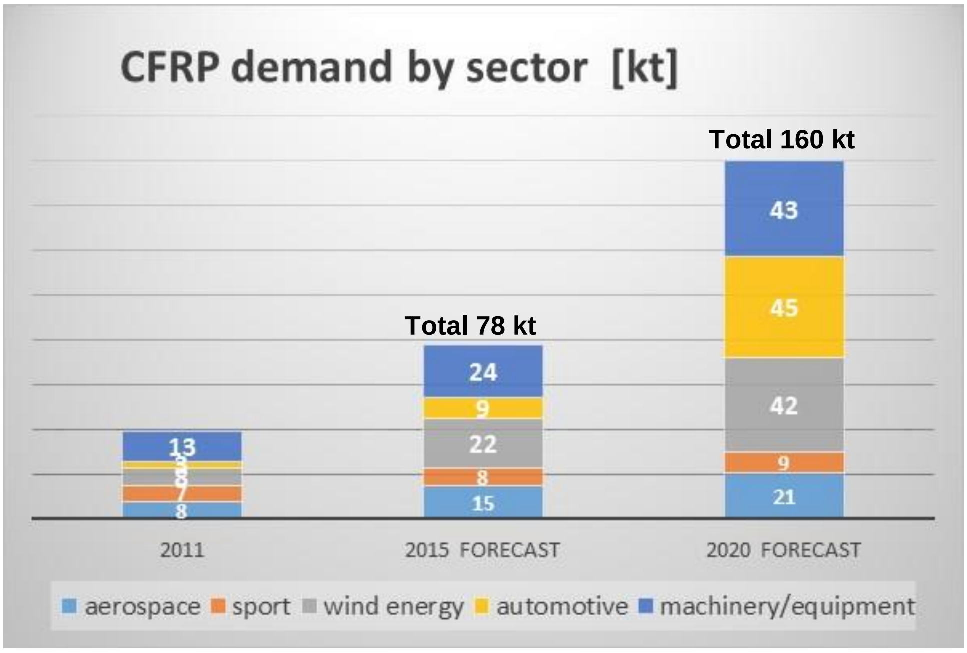
Figure 21: Global demand for carbon fiber in 1,000 tons from 2009 to 2021



Source: M-Five based on Acmite Market Intelligence 2016

Figure 22: Global production of carbon fiber by region in 1,000 tons for 2015 to 2024

Demand forecast for CFRP by sector have been prepared in 2012 (Lässig et al. 2012). They expected a market of 78 kt in 2015 and of 160 kt in 2020. For 2015 this is broadly consistent with the observed values. In 2020 it is expected that the automotive sector reveals the highest demand for CFRP, closely followed by the machinery sector and the wind energy sector. Since 2011 the automotive sector then would have revealed the highest growth rates (35% CAGR), but starting from a comparably low base value in 2011.

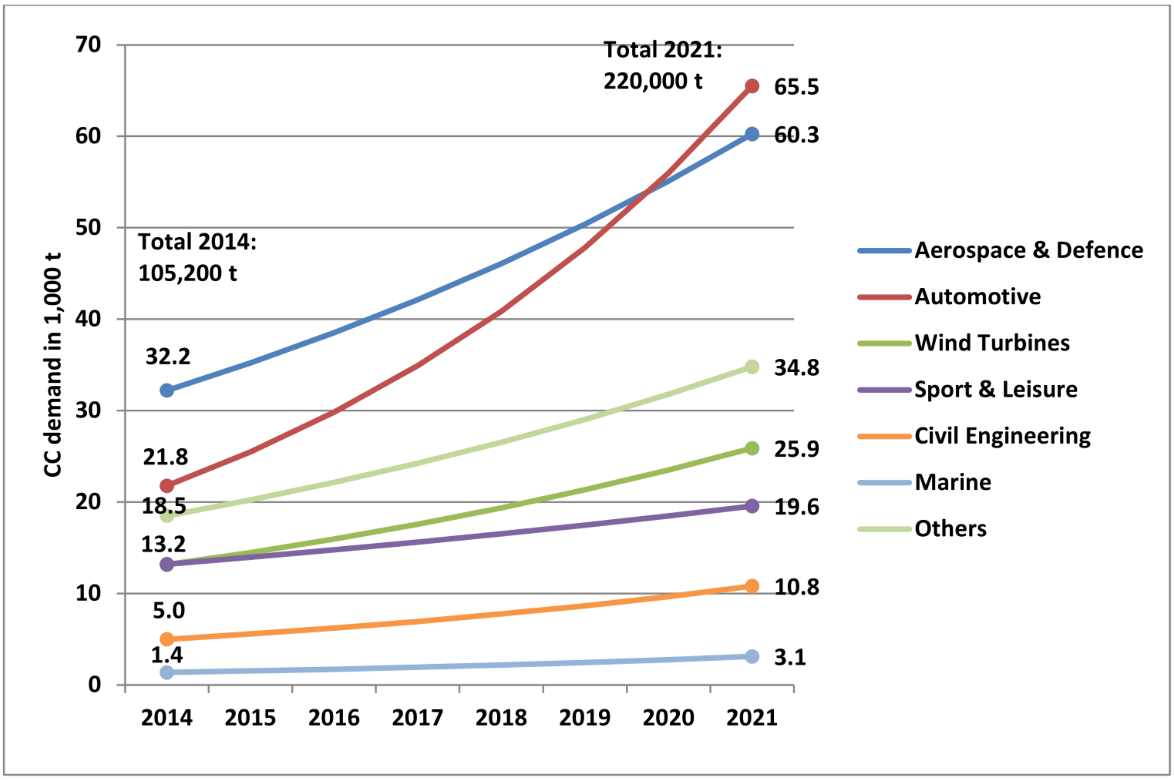


Source: M-Five based on Lässig et al. 2012

Figure 23: Global demand for CFRP in 1,000 tons until 2020

The growing importance of the automotive sector is consistent with the forecast of carbon composites of the German experts shown in Figure 24 (Krause et al. 2015). For 2021 they expect a demand of 220 kt CC of which roughly two third would be CFRP such that this demand forecast seems broadly in line with the previous one. In 2020 the automotive CFRP demand is surpassing the demand of the aerospace & defense sector becoming the single largest demand sector for CC as forecasted as well by the Roland Berger experts (Lässig et al. 2012). However, calculating a rough estimate of a hypothetic average carbon content of cars in 2021, the average weight of CFRP in a car would remain in the 1-digit kg range. With 50% saving of weight by CFRP the average saved weight of a car by CFRP would be in the same order of magnitude.

Again we would like to point out that these market forecast adopted price reductions of CFRP and CF much lower than those most recently expected and envisaged to be achieved by new processes and by patents filed. This indicates that these demand forecast could even be outnumbered by 2020 due to the stronger price decreases.



Source: Kraus et al. 2015

Figure 24: Predicted CC demand in 1,000 t by application up to 2021

Besides CFRP and GFRP, **natural fiber** reinforced plastics play an increasingly important role in the fiber composite plastic segment. From the customer's perspective, the specific material characteristics are generally decisive. Natural fiber reinforced composite plastics are classified as bio materials and are mostly used in the automotive, construction and furniture industry, whereas CFRP are primarily used in aviation, wind power plants, sports and transportation. Some forecasts might have underestimated the opportunities provided by natural fibers reinforced plastics (AVK - Industrievereinigung Verstärkte Kunststoffe e.V., 2014).

Along with the market studies and demand forecasts Composites Germany regularly publishes a **composite market survey** based on a questionnaire it sends out to all the member companies of the four its biggest umbrella organizations (Composites Germany, 2016) since 2013. The market survey provides a qualitative picture of general market developments and also of the specific developments of the various composites segments. Since the first edition of the survey in 2013, the level of satisfaction among participating companies was generally very high (Begemann, 2016). The survey assesses the general business situation, the companies' own business situation, the investment climate, and the drivers of growth and generates a composites index on this data. 82% of respondents stayed optimistic or very optimistic concerning the global market of the composite industry. For the German market even 87% show this expectation. The major driver of growth was seen with the Carbon Fiber Composites used in the aerospace and the transport sectors. 44% of the participants expected investments in machines and plants in the first half of 2016, which is an extremely high value. Furthermore, over half of the participants expected a stronger engagement of their company in the composite sector.

Not all European countries share this positive outlook. The Swiss network of plastics stakeholders Swiss Plastics has published an innovation report on the competitiveness and power of innovation of the **Swiss plastics industry** in 2014 (Swiss Plastics, 2014). Based on the shrinking consumption of resources, a weak foreign trade balance, shrinking margins and a negative development of the real value added, the network prognosticates difficult times for the Swiss plastics industry. Concerning fiber-reinforced composites, the authors consider the difficulty to automatically produce great volumes at constant quality as the major obstacle to a further industrial dispersion. The report takes a closer look at the potential of fiber-reinforced thermoplastics whose potential can be exploited for the production of automotive carbon wheels. According to the authors, the technologies serving the serial production of carbon wheels enable the production of numerous other components, so that the production lines can easily be adapted for other purposes. The more thermoplastic applications find their way into serial production, the lower the prices of production and for the prepreg production, so that cost advantages are to be expected in the future (Swiss Plastics, 2014). This conclusion was prevalent in several analyst reports of 2013/2014, though we do not share it as recent patents, product and process innovations point rather to a success story of CF and CFRP, in particular for automotive uses.

3.4.3 The role of automotive market for CF and CFRP

The CFRP market forecasts by 2020 expect the highest market share to account for the automotive sector. This section takes a closer look at the link between automobile market strategies and model cycles and the CFRP market. In general, expensive innovations are first implemented in high-end cars and with the cost of the innovation decreasing due to technological learning and economies of scale the innovation starts to diffuse also in high-volume lower cost cars. The same is expected to hold for CFRP with the exception that for strategic reasons they could be implemented as well in electric vehicles at an early stage of the CF/CFRP market development.

Figure 25 provides for a simple estimate of automotive CF demand based on the forecast of global new car sales in 2018, the market segmentation into super cars, super luxury cars, luxury cars and regular cars and assuming certain shares of this new fleet would be equipped with CF material. At a CF price of 22 to 26 $/kg the demand would reach 537 kt of CF leading to a market of more than 14 billion US$. The demand would be about sevenfold the values in the demand forecast that we identified above (e.g. Figure 21). Presumably, it is the high share of CF/CFRP per car that the authors assumed which exaggerates the demand. However, the estimate reveals that it need not be extraordinary shares of the automobile market that adopt CF/CFRP parts to drive demand. A 10% share of super luxury cars and luxury cars equipped with CF/CFRP seems at the very low end of expectations for 2018.

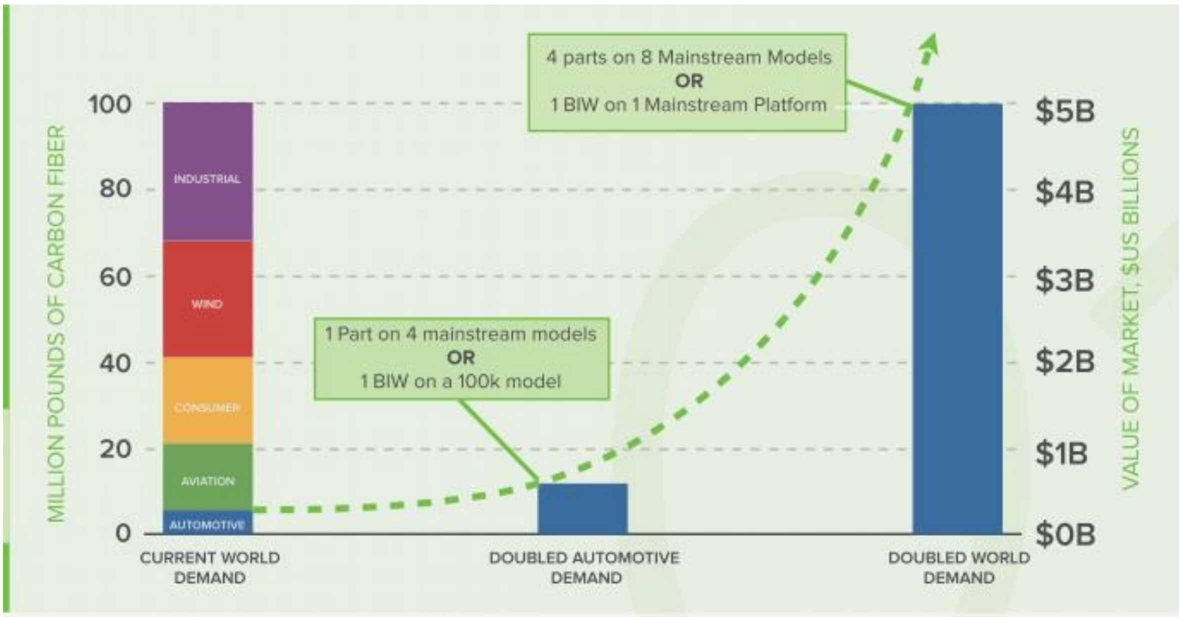
Global Automotive Production Forecast by Car Type in 2018		Expected Demand of CF @ Current Price in 2018			Expected Demand of CF @ $5/lb in 2018		
		CF Usage in % of cars	Demand in Mlbs	Demand in $M	CF Usage	Demand in Mlbs	Demand in $M
Super Cars	*6,500*	*100%*	*1.43*	*17.2*	*100%*	*1.43*	*7.2*
Super Luxury Cars	*650,000*	*10%*	*14.3*	*172.0*	*25%*	*35.8*	*179.0*
Luxury Cars	*5 Million*	*10%*	*110.0*	*1,320.0*	*25%*	*275.0*	*1,375.0*
Other/Regular Cars	*96 Million*	*5%*	*1,056.0*	*12,672.0*	*10%*	*2212.0*	*10,560.0*
Global Automotive Production in 2018	*102 Million*		*1,182*	*14,181*		*2424*	*12,121*

Assumption: Per vehicle CF consumption is 220 lbs

Source: Mazumdar 2013

Figure 25: Carbon fiber potential with diffusion of CF/CFRP parts into different car segments

A similar thought experiment was provided by the Rocky Mountain Institute in the same year (RMI 2013). They explained that out of 1,400 models it requires just 1 part in 4 mainstream models to be produced from CF to double automotive demand for CF. With 4 parts on 8 mainstream models the annual automotive demand would reach the same level as the whole CF demand in 2013 (see Figure 26).



Source: RMI 2013

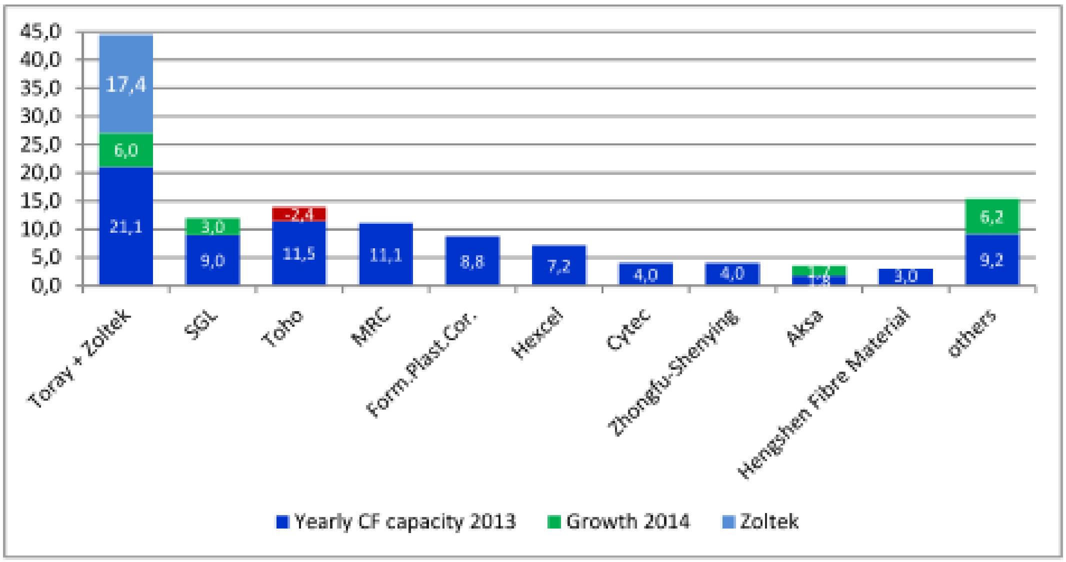
Figure 26: Examples of market impacts of producing certain parts of cars by CFRP

In 2013 about 80% of the CF demand came from two models: 74% from the BMW i3 and 6% from the Chevrolet Corvette Stingray (CEMAC 2016). Since then, significant progress has been made. For instance BMW is producing safety relevant parts like the C-pillar for the BMW 7series from CF today as well as roofs for the M3 and M6 models saving 5 kg compared with the conventional steel version, at a weight of 4,5 kg of the CFRP part. Given that the BMW 7 series achieves an annual production of 100.000 it would be that the middle blue bar in the estimate of RMI (see Figure 26) was reached or even outstripped.

3.4.4 CF manufacturers

In 2013 a VDI study concluded that the **market** of carbon fibers for CFRP is dominated by the US-American suppliers Zoltek and Hexcel and the Japanese suppliers Toho, Toray and Mitsubishi Rayon. The only German supplier SGL Carbon was on sixth position with an annual capacity of 7.000 tons of CF. Chinese carbon fiber producers were not playing a significant role, but would be entering the market with massive announced capacity increases (Eickenbusch and Krauss, 2014).

Figure 27 presents the CF production capacity by manufacturer for 2013 and 2014. It reveals that the CF market structure may change substantially from year to year. In 2014 Toray (Japan) has increased its production capacity by 6 kt and acquired the second largest manufacturer Zoltek (US) to become the dominant manufacturer with 36% of market share (Kraus et al. 2015, see also CEMAC 2016). Actually SGL became the second largest manufacturer due to its investment in additional capacity, and contrary to other manufacturers that supply to all sectors or are specialized in aerospace SGL is clearly focusing on the automotive market. Another relevant player should be Mitsubishi Rayon Co. (MRC) who is the only CF manufacturer active in all steps of the value chain from the raw materials of the precursors, the precursors themselves, the CF to prepregs and CFRP. In terms of capacity MRC is ranked about 3rd and is also manufacturing CF in Germany (CEMAC 2016).

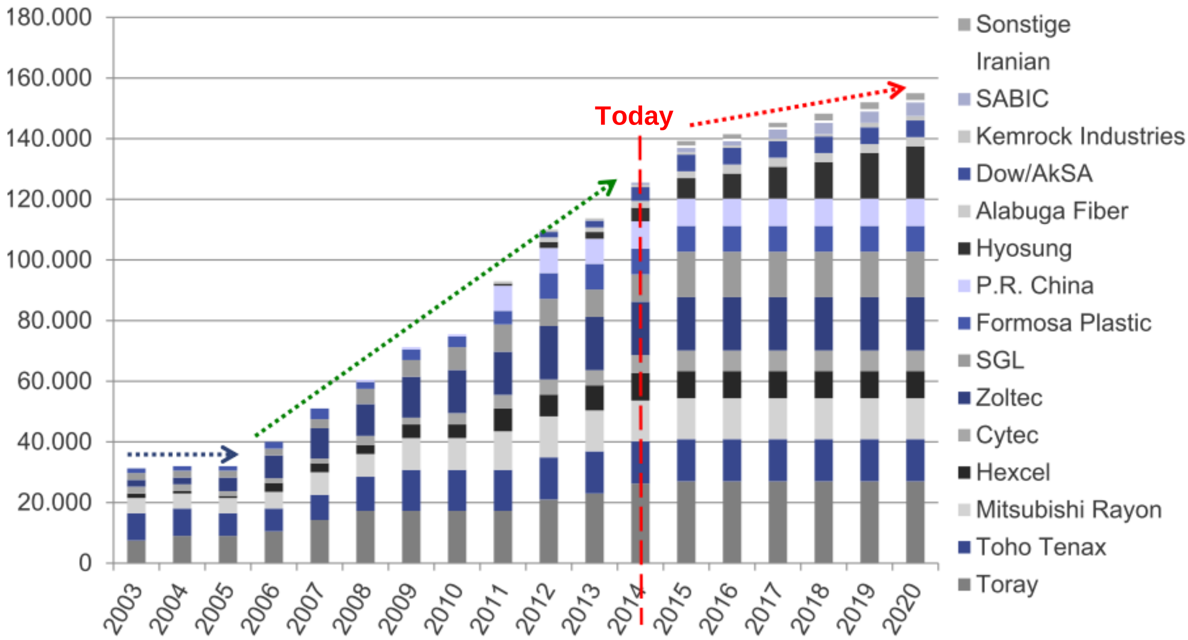


Source: Kraus et al. 2015

Figure 27: Global CF production capacity in 2013 and 2014 [in kt]

In 2012 only four manufacturers produced the large tow fibers that are used in automotive applications: Toray/Zoltek, MRC, Hexcel and SGL. The large tow capacity amounted to 37% of total CF manufacturing capacity (CEMAC 2016).

The following Figure 28 illustrates the trends of global production capacities of carbon fibers in tons (Herbeck 2014). Since 2006 until 2014 there has been a significant growth of production capacity as well as that several new entrants have entered the market. This includes Hyosung a manufacturer from South Korea and SABIC a manufacturer from Saudi-Arabia a country that due to its availability of raw materials for precursors and cheap (renewable) electricity potentials also expects to have market opportunities in the CF market.



Source: Herbeck 2014

Figure 28: Carbon fiber production capacities by manufacturer [t]

In 2005/2006 it came to a shortage of CF during which prices went up temporarily. The limiting factor was the availability of polyacrylonitrile fibers (PAN) which serve as a precursor for the production of carbon fibers. The growth of capacity and the decrease of demand during the crisis of 2008/2009 relaxed the situation, but shortages are still seen as a possibility in the coming years. Therefore, any OEM and in particular German OEMs with a more limited domestic supply base than in the US are making sure to secure sufficient availability of high quality fibers when planning for increased use of CFRP. Besides the extension of production capacities, the development of processes for the production of fibers on the base of alternative precursor materials then PAN and of recycling processes represent important ways to overcome this potential market barrier for CFRP. System competence, technological knowhow and strategic cooperation with global partners are deemed to be decisive for a secure access to fiber capacities (Eickenbusch and Krauss, 2014).

3.5 Actors of CFRP value-chain in Germany

Germany in 2014 hold a share of about five percent of the global carbon fiber production, just behind South Korea, Hungary, Taiwan and China (see Figure 16). The German OEM have all established relationships with supply chains and cooperations for their CF demand to guarantee secure supply of CF and fabrics. The most prominent supply chain from BMW starting with MRC in Japan (precursor) and involving SGL ACF in the US (CF) and ending in Wackersdorf (fabric), Landshut (CFRP part) and Leipzig (assembly) in Germany was explained in section 3.3. As a strategic element of the supply chain BMW has established a joint venture with SGL, the SGL Automotive Carbon Fibers (ACF). Also BMW and Volkswagen hold shares on the SGL Group (as of July 2016 18,44% and 9,82%, respectively), which in the case of BMW is further extended by shares of a joint shareholder of BMW and SGL Carbon (27,46%). Similar joint ventures exist between Daimler AG and Toray Industries and between Audi AG and Voith Composites GmbH & Co. KG since 2011 (business news and Schade et al. 2012).

Further examples of relevant business actors in Germany producing CF or CFRP parts include Benteler-SGL with manufacturing sites in Germany and Austria and owned by Benteler Automobiltechnik and again the SGL Group. Also the 3C-Carbon Group AG from Landsberg and the Polytec Composites Germany GmbH & Co KG with two locations supply to the automotive sector.

Additionally there has been developed a complex innovation system of German research institutes, Universities, associations and large scale research projects to develop innovations and new applications for CF and CFRP. The major stakeholders in the German-speaking fiber-reinforced innovation system are the Carbon Composites e.V. association, the cluster of excellence MAI Carbon, the Federation of Reinforced Plastics AVK e.V., the association CFK Valley Stade e.V. (CFK-Valley) and the VDMA Working Group Hybrid Lightweight Technologies.

Carbon Composites e.V.[10] is an association of 250 member companies and research institutions, covering the entire value added chain of high performance fiber-reinforced composites in Germany, Austria and Switzerland.

Composites Germany[11] is the trade association of the four major organizations in the German fiber composite industry AVK- Federation of Reinforced Plastics e.V., Carbon Composites e.V. (CCeV), CFK Valley Stade e.V. (CFK-Valley) and Hybrid Lightweight Technologies. Composites Germany is a member of the **European Composites Industry Association EuCIA**[12], the Brussels - based leading Association of the European composites indus-

[10] http://www.carbon-composites.eu/

[11] http://www.composites-germany.org/index.php/en/

[12] http://www.eucia.eu/

try, representing European National composite associations as well as industry specific sector groups, such as those targeting end segments like automotive or those promoting particular product groups or processes.

MAI Carbon[13] is a German cluster of excellence (also known as leading-edge clusters) aiming at the industrial implementation of carbon-fiber reinforced plastics by 2020. Initiated by the association Carbon Composites e.V., its founding members include Audi, BMW, Premioum Aerotec, Eurocopter, Voith, SGL Group, IHK Schwaben and the chair for carbon composites of the technical university of Munich. The cluster bundles almost 100 partners and receives funding from Airbus and from the German Federal Ministry of Education and Research. Their objective is to develop the readiness of CFRP for large series production and to turn the region into a European center of competence for CFRP lightweight construction, automotive construction being one of the central areas of application. In different research projects, topics along the entire value chain include:

- the development of a continuous process chain for the production of fiber composites with a thermoplastic matrix for large series applications;
- the development of new preforming technologies enabling the quick production of preforms directly from the roving and thus minimizing offcuts;
- the development of methods for a faster, automated and nondestructive testing for quality management and reduction of scrap rates;
- optimization of the process steps for the production of carbon fibers; development of technologies for the production of carbon fibers from alternative precursor materials such as of the biopolymer lignin;
- development of a complete process chain for the recycling of production scrap and mixed CFRP residues.

A holistic consideration along the entire design and production process shall develop an understanding of materials and structures for the optimized utilization of CFRP in the respective application. The development of processes in MAI Carbon is focusing on the refinement of the RTM process in order to achieve the breakthrough of large series production. For instance, the objective of one project is to achieve an annual production of 100.000 endless-fiber-reinforced structural components with complex geometries at a cost of below 80 €/kg and at a cycle frequency of five minutes (Eickenbusch and Krauss, 2014).

The **DFG[14] research group FOR 860** also pursues the objective of the development and realization of large series production chains for high-performance fiber composite components. Researchers of the RWTH Aachen and of the Fraunhofer Institute for Production Technology are working on technologies along the entire value chain of textile preform production, impregnation, forming and cross-linking as well as handling and tool technology. A focus is the development of a multiple preforming process for the production and processing

13 http://carbon-composites.eu/de/netzwerk/abteilungen/mai-carbon/?pk_campaign=www.mai-carbon.de&pk_kwd=/

14 DFG is the German Research Foundation funding largely basic research as well as some applied research.

of complex near-net-shape preform geometries via the mounting of simply formed preforms in an automated process chain (Eickenbusch and Krauss, 2014).

The **AVK Industrievereinigung Verstärkte Kunststoffe e. V. und AVK-TV GmbH**[15] is the industrial federation of the German composite plastics industry: "The AVK currently has over 220 member companies and is therefore one of the largest associations in the European composites sector. It represents members along the entire value-added chain in the area of reinforced plastics. Its members include manufacturers and suppliers of raw materials as well as processing companies, machine-tool manufacturers, engineering firms, testing authorities and scientific institutions. The association represents both small and medium-sized companies as well as major multinational players."

The **VDMA Forum Composite Technology** was a network of over 170 engineering suppliers for composite manufacturing with the German Engineering Federation VDMA serving as an interface to all companies, associations and institutions being involved in manufacturing, processing and applying composites. In 2016, it has been incorporated into the **VDMA Working Group Hybrid Lightweight Technologies**[16] which includes carbon composites production but is not focused on it.

The **alliance for fiber-based materials Baden-Württemberg AFBW e.V.**[17] is a network of scientific and economic actors supported by the Ministry of Economy, Labor and Dwelling of the Land of Baden-Württemberg and by the European Fund for Regional Development (EFRE). Further agents of this region include **Carbon Composites Baden-Württemberg CCBW**[18] and the **Center for lightweight construction Baden-Württemberg LBZ**[19]. These agents jointly organize the annual Technology Day Hybrid Lightweight Construction[20].

The Cluster for New Materials of the Bayer Innovativ GmbH organizes the **yearly symposium Material Innovativ**[21] at which trends and developments for the mobility of tomorrow are presented by companies and experts. Also, the Association of German Engineers (**VDI)** organizes a yearly **congress for lightweight construction**[22] since 2010. This year's topics were:

- lessons learned by OEMs in mixed material construction.
- lightweight construction in the context of the whole vehicle and customer factors.
- intersectoral lightweight construction concepts and competition of technologies in the automotive and aeronautic industry.

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15 http://www.avk-tv.de/

16 http://lightweight.vdma.org/

17 http://www.afbw.eu/en/

18 http://www.carbon-composites.eu/de/netzwerk/abteilungen/cc-baden-wuerttemberg/

19 http://www.lbz-bw.de/

20 http://www.leichtbau-bw.de/aktuelles/technologietag-2016.html

21 http://www.bayern-innovativ.de/material2016

22 http://www.vdi.de/leichtbau

- recycling strategies and additive manufacturing – transfers from small to large series.
- industry developments in lightweight construction – new technology concepts.
- research activities international – significance for the technological site Germany.

The Chair for Carbon Composites of the Technical University of Munich and companies like Airbus have developed a software, which designs complex components in a way that they can be easily produced and mounted automatically. The start-up **Cevotec GmbH**[23] was founded in 2015 and has been granted almost two million Euros of private funding for the further development of this procedure (Jakob, 2016b).

Further research organizations contribute to the innovation system of CFRP. For example, the **Fraunhofer ICT**[24] is working intensely on the improvement of the production and process technology for the production of high performance components with a duroplastic matrix such as epoxide and phenol resins. Research is especially focusing on the utilization of micro waves for improving the flowability of the resin and for an improved infiltration of the fiber structures, but also the micro wave assisted cross-linking of duromer resins (“cure on demand”) (Eickenbusch and Krauss, 2014). Thermoplastic high performance fiber composites have a particularly high potential for large series lightweight vehicle construction. The composite is here fixed via purely physical cooling processes and is therefore much faster than the hardening of duroplastic. In order to seize this advantage, Fraunhofer ICT is working on so-called T (for thermoplast) -RTM processes during which the matrix system polymers in the tool. This has advantages concerning the infiltration and impregnation of the fiber reinforced structures and thereby enables higher filling grades. This process shortens the cycle times of different thermoplastics to few minutes.

In general, it can be concluded that CF and CFRP production in Germany is feasible. A few actors contribute to the first steps of the value chain (CF precursor, CF production, resins etc), while the number of actors increases along the value chain and is also high for producers of machinery to produce CFRP parts. There are even examples amongst the producers of machinery like Dieffenbacher GmbH who have given up their business in the metals machinery sector and have shifted to produce machinery for CFRP production. To achieve these goals Dieffenbacher partners with research institutes (e.g. Fraunhofer ICT) and has also acquired foreign know-how by buying the Fiberforge technology from the defunct Fiberforge company that in the past had been founded by the Rocky Mountain Institute to foster the development of lightweight technologies.

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[23] http://cevotec.com/

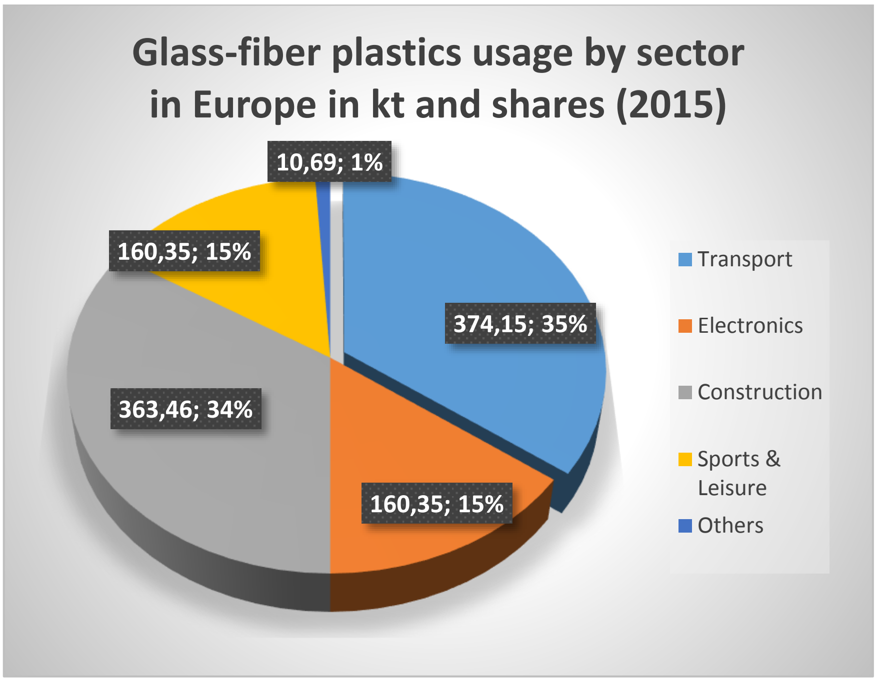
[24] http://www.ict.fraunhofer.de/

4 Glass fiber reinforced plastics (GFRP)

Often referred to as fiberglass, GFRP is less strong, stiff and brittle than CFRPs and its raw materials are much cheaper. Glass fiber composite currently represent 95 percent of all fiber composites. In Europe, over one million tons of GFRP are being produced each year. The large series production processes *Sheet moulding compounds* (SMC) and *Bulk moulding compounds* (BMC) hold a share of 25 percent of this production. The applications are dominated by the transport and construction sector with about 35 percent each, followed by electronic and sport/leisure with about 15 percent each (Woidasky, 2013).

Glass fibers are the oldest and, by far, the most common reinforcement used in non-aerospace applications to replace heavier metal parts. Glass weighs more than carbon, but also is more impact-resistant. Depending upon the glass type, filament diameter, sizing chemistry and fiber form, a wide range of properties and performance levels can be achieved. The characteristics which make GFRP useful for automotive purposes are its total non-inflammability and the colorability of the glass-fibers. Furthermore, damages of the laminate can be recognized optically, which is barely possible with CFRPs. Its almost ideal-elastic behavior and the low elasticity module are not suitable for the majority of structural applications. For suspension elements however, these characteristics are desired and GFRP is therefore already being employed in their serial production (Grillitsch, 2013). A prominent example is the GFRP leaf spring, which is used in VW's and Mercedes' small transporters Crafter and Sprinter. This lightweight component weighs only five kg, which is only 20 percent of the conventional leaf spring made of steel. The producer IFC Composite in Haldersleben has meanwhile developed a prototype GFRP leaf spring for trucks of up to 40 tons which can reduce their weight by almost 100 kg (Eickenbusch and Krauss, 2014).

In 2014 in total 8.8 million tons of plastic composites have been produced globally out of which 2.3 million tons were produced in Europe (26%). About one million tons of these plastic composites from European production have been GFRP with the transport sector demanding 374 kt (see Figure 29).



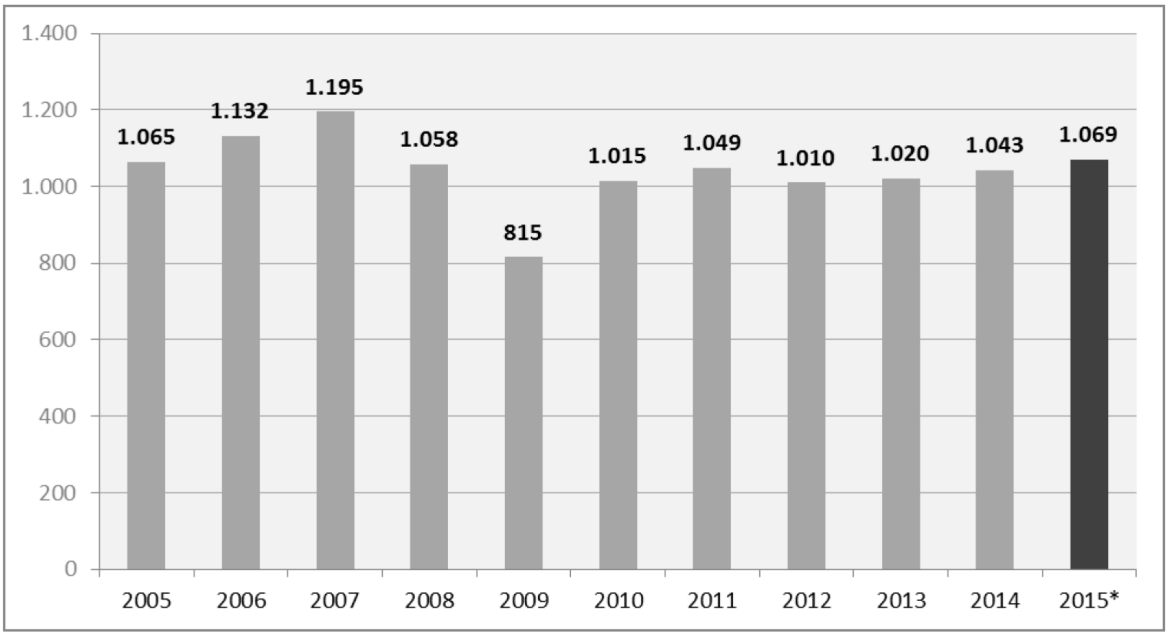
Source: Kraus et al. (2015)

Figure 29: Glass fiber reinforced plastic demand by application in Europe

The production of GFRP by closed RTM procedures still grows at rates above average in Europe. These procedures substitute existing open procedures more and more. The advantage of the new procedures is the possibility to produce surfaces, which are plain on both sides. The so-called pultrusion procedures are used to produce GFRP-profiles for the transport and construction industry (bridges, cable channels). The winding and centrifugation procedures are used for the production of tubes and tanks. Besides these applications with a duroplastic matrix, in the automotive industry thermoplastic molding bathes and materials are dominating the automotive sector. These build on short- and long-fibers as well as glass mat reinforced thermoplastics. The latter primarily for high-performance composite materials (AVK - Industrievereinigung Verstärkte Kunststoffe e.V., 2014).

Germany, UK / Ireland as well as Eastern Europe are the **European regions** with the highest growth rates. Germany as the major European producer of GFRP and composites experienced a six percent growth in 2015, resulting in a total production of 212 kt. Considered Eastern European countries grew by four percent and UK / Ireland by almost three percent. The Scandinavian countries were the only ones with a shrinking production, whereas other countries with low absolute production levels were stable (Austria, Switzerland) or experienced moderate growth (BeNeLux). In the Southern European countries, the development of the recent years continued: Spain, Portugal and Italy experienced weak growth rates whereas stagnation continues in France. These market movements can be explained by the developments in core industries such as automotive and maritime construction as well as construction and infrastructure. Light economic growth will also have an effect on the GFRP industry. Growth in Turkey was slightly lower than in former years with about 2 percent. The largest potential of growth is seen in the largest applying industry of tube and tank production for infrastructure projects, where the potential of new plants continues to be important. Automotive and transport construction represented another driver of growth (Kraus et al., 2015).

The following Figure 30 illustrates the amount of GFRP produced in Europe during the past ten years. Actually the production is stagnating, despite slow global growth of GFRP demand.



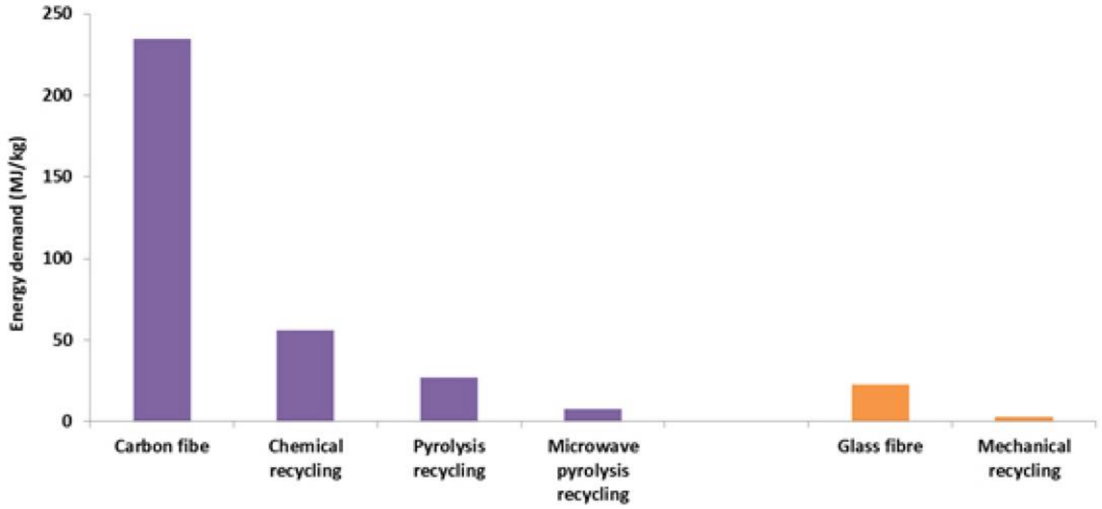
Source: Kraus et al. (2015)

Figure 30: Glass fiber reinforced plastic production in Europe [kt], 2005 to 2015

The previous paragraphs have revealed that the GFRP production in Europe is stagnating since roughly a decade. This situation is much different from the one of CF and CFRP. It seems that despite lower cost the material characteristics are not sufficiently attractive to stimulate growing use of GFRP. In fact, as reported by BMW (see section 3.3) and also possible to conclude from the literature on recycling the progress of CFRP seems to displace the increased use of GFRP. Therefore, we would not recommend to integrate specific scenarios or elements of the scenarios depending on GFRP production and use.

5 Recycling of fiber composites – focus CFRP

Carbon fibers are still an expensive component of CFRP unlike glass fibers that cost a fraction of CF. Therefore it is commercially viable to establish recycling processes of CF. Figure 31 presents energy demand for producing carbon fibers (left hand bar) as well as the energy demand for different recycling processes of CF. The pyrolysis process consumes about one tenth of energy of producing virgin CF. Therefore CF recycling also provides for ecological advantages.



Source: Job et al. 2016

Figure 31: Comparison between embodied energy of fiber production and potential recycling processes (average)

Two important factors have to be considered when analyzing the opportunities of CF recycling:

- Cost of the recycled CF in relation to virgin CF.
- Quality of the recycled CF.

One of the first industrial applications of CFK recycling was implemented in 2011 at the recycling center of the **CFK Valley Stade.** The recycling process builds on pyrolysis. In a first step, the dry carbon fiber scrap and prepreg materials are sorted and comminuted. The pyrolysis process then dissociates the matrix material at temperatures between 400 and 1.000 degrees C. In order to protect the fibers from contact with oxygen, the process happens under protective atmosphere. The director of the facility explains that the fibers are of the same quality as in the CFRP part. However, as in the CFRP part the fibers might have been cut already their quality is deemed to be lower than of virgin CF by customers. Nevertheless the CF are suitable for multiple other applications such as electronic housings, machine construction or interior sheeting and come at a price about 50 to 60% lower than comparable new fibers (Eickenbusch and Krauss, 2014 and CFK Valley information).

In the context of MAI Carbon, the project **MAI Recycling** is aiming for a continuous process chain from production scrap and mixed residues until the recycled carbon fiber for the reuse in different products is extracted. Different splitting processes such as pyrolysis and solvolysis have been investigated and optimized. The development of analyzing, classification and recovery methods was also part of the project. Finally, products for the ecological and economical deployment of the fibers have been tested. The findings were less promising then at the Stade facility. During the recycling processes a significant share of CF gets lost and CF may also be damaged by the various process steps (MAI Recycling 2015).

Currently, pyrolytic processes are considered as the most developed ones. But chemical procedures for the separation of matrix and fibers such as **solvolysis** also represent an important and promising activity of research. In this process, the matrix material is dissolved into a liquid recyclate by reactive resolvents without destroying the carbon fibers. This procedure is being investigated in a research project financed by Boeing at the University of Nottingham using hypercritical fluids. The challenge is to not damage the fibers during the thermic solvolysis whilst using the most ecological resolvents. Such chemical recycling procedures are still in the status of R&D and not yet industrially applicable (Eickenbusch and Krauss, 2014).

Composites UK has recently published their new report[25] on composites recycling. It gives an overview on the current recycling processes available for carbon and glass fiber waste and highlights future steps which need to be taken in order to make these processes more commercially viable. They conclude that glass fiber recycling will not economically viable because of the low cost of these fibers and the loss of fiber quality during the recycling process. However, for CFRP they confirm the success of CFK Valley Stade Recycling in Germany and ELG Carbon Fibre in the UK to provide high quality recycled CF, though again the quality is lower then of virgin CF (Jobs et al. 2016).

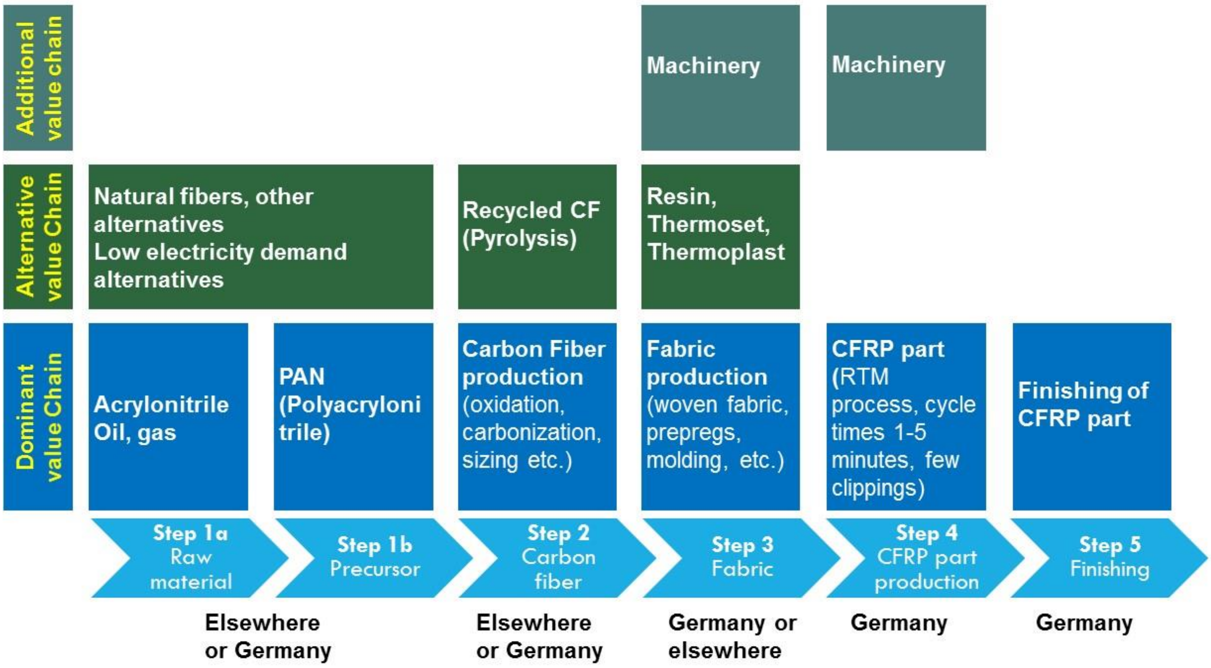
In summary, CFRP parts recycling will provide CF at significantly lower cost than virgin CF and using a fraction of energy, only. The quality of recycled CF will be lower than of virgin CF, such that the recycled fibers should be used for parts with lower requirements on stiffness and stability.

6 Criteria for selection of manufacturing sites for CFRP value chain

There have been identified a few criteria that would determine decisions on manufacturing locations of the CFRP parts value chain. First of all, there is the availability of raw materials and of cheap electricity, which is in particular relevant for the carbon fiber production. However, these criteria could change with technological advancements. One option is that production of the precursor PAN gets less energy intense such that the electricity price becomes less decisive. A second option would be that alternative fibers do the same job as those made out of PAN e.g. with using natural fibers that process step would become less energy intense as well. A third option would be that recycling processes improve and a significant proportion of CF could be supplied from recycled CF. It is estimated the recycled CF would require only 10% of energy as opposed to PAN based CF. Such options are shown in Figure 32. The value chain with the blue boxes describes the dominant value chain with PAN based CF and an improved RTM process with short cycle times enabling mass production of CFRP parts. Taking the BMW i3 value chain as a blueprint and assuming no substantial technological progress step 1 would take place in Japan, step 2 in the US and Step 3 to step 5 in Germany. Variants of the value chain could either (1) consider some of the green boxes indicating alternative technologies and technological progress modifying the value structure

[25] https://compositesuk.co.uk/recyclingreport

of some steps, or (2) shift some of the steps undertaken in Germany to another location or vice versa, e.g. assuming that CF production could also take place in Germany.



Source: M-Five

Figure 32: CF and CFRP alternative value chains

A second relevant criteria for location choice concerns labour cost. The US analysis of CEMAC (2016) revealed labour cost share of 7.5% for step 1+2, of 14% for step 3 and of 24% for step 4. However, the highest labour costs are observed in Germany by this analysis but still the labor costly steps 3+4 are actually located in Germany. The reasons could either be (1) that other factors that counterbalance high labour cost play a more prominent role like high skill requirements of labour, or (2) that the labour cost shares refer to older technology then applied by the German manufacturers, in particular BMW and SGL ACF. We assume the second reason to be valid.

It can also be considered that shipping plays a negligible role at least until step 3, and that in general having step 4 and step 5 close to the research and design centers and/or close to the manufacturing site of OEMs is deemed to be reasonable if not even necessary. Thus step 4 and step 5 can be expected to locate in Germany. The question remains then about the location of steps 1 to 3.

There are several alternatives to design different structures of the value chain as Figure 32 also indicates by the green boxes of alternatives and additional elements of the value chain:

1. Step 3 production not in Germany if more standardized products emerge and OEMs (and their joint ventures) do not intend to have a competitive advantage due to developing and using their own fabrics.

2. Step 2 production also in Germany because of recycling CF becoming a low cost and low energy option in the future.
3. Step 2 production also in Germany because natural fiber technologies improve and can be used in the same way as PAN based CF.
4. Step 3 and step 4 could also be linked with a scenario in which the German machinery producers will provide the equipment for the manufacturing sites generating additional value.
5. Additionally it could be assumed that the machinery sector gains a lead market advantage by the previous scenario assumption (4) enabling additional exports of fabric and RTM machinery.
6. A general shift in value share from the left hand side to the right hand side. While the German analysis indicated a 70% value share in steps 1+3, the US analysis saw a 70% value share in steps 4+5. The US analysis is undertaken more recently and we deem it more appropriate. It also fits better for scenarios in which German industry fosters CFRP part production as their value share will then be larger.

7 Diversity of expectations and the valley of death

At the beginning of the project a number of stakeholders was optimistic on the future potential of CFRP for use in automotive manufacturing. Actually our analyses also found some evidence that the competitive position of CFRP over the last few years has improved and we believe that the material bears the potential for disruptive change in the future.

However, in the course of the project the stakeholders expressed concerns on the potential of CFRP and rather expect light-weighting to develop by incremental improvements as we observe them today applying hybrid light-weighting using a mix of materials (e.g. HSS, AL, MG, GFRP, CFRP).

Our interpretation is that CFRP today have reached their valley of death. According to innovation theory technological innovations develop in cycles in which high expectations in relation to the potential of a new technology alternate with periods of low expectations. Innovations may also be stimulated by government-funded basic research. The valley of death occurs when a technology fails to move on from basic research stage to commercialization. This depends on the expectations of entrepreneurs. With low expectations of the entrepreneurs an innovation might never cross this valley of death from research to commercialization and would then be discarded as a potential solution for the future. Stakeholders today seem to be disappointed by the progress CFRP have made in relation to cost reductions, cycle times, GHG balance and recyclability. Therefore CFRP seem to be stuck in the valley of death, at the moment, at least in what concerns their widespread use in the automotive sector.

Nevertheless, we still consider CFRP to be a promising light-weighting option bearing the potential for future disruptive change in the construction of light-weight cars. In our view CFRP in the future could survive and emerge from their valley of death. For instance, this could happen via developments taking place in the construction industry as in 2016 the most renowned German award in technological innovation (”Deutscher Zukunftspreis”) went to “carbon concrete”, which is a construction material replacing steel in ferroconcrete by carbon fibres.[26] Other weak signals come from the machinery manufacturers where the first German companies are giving up their metal machinery business in favor of extending their CF/CFRP machinery technology business.

8 Scenarios of future manufacturing strategies for the project

The basic conclusion for the project is that Germany is in a position to apply different lightweight technologies and to capture a share of their value chains similar to shares of current materials. Therefore the analysis of lightweight technologies is not suggesting to apply additional alternative scenarios in the project on *Low-carbon cars in Germany*.

We have highlighted that CFRP bears the potential for disruptive change in the period up to 2030. In the case that scenarios of disruptive change in CFRP technology and thus cost reduction should be modelled and given that the project already analysed many scenarios we would suggest to limit the number of scenarios linked with CFRP. The focus of such scenarios should be on two variants that both substantially increase the share of CFRP in car weight but differ in the location of the fabric production of CFRP (step 3 of the value chain in Figure 32).

- **Baseline CFRP scenario** (DE-Fabric): Fabric production takes place in Germany (BMW i3 value chain).
- **Alternative CFRP scenario** (US-Fabric): Fabric production moves to countries with low electricity prices and lower labour costs (e.g. US). For German industry this would mean a loss of 15% of the value chain of CF/CFRP parts production.

[26] A description on carbon concrete in English can be found here : http://www.deutscher-zukunftspreis.de/en/nominated/2016/team-1.

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