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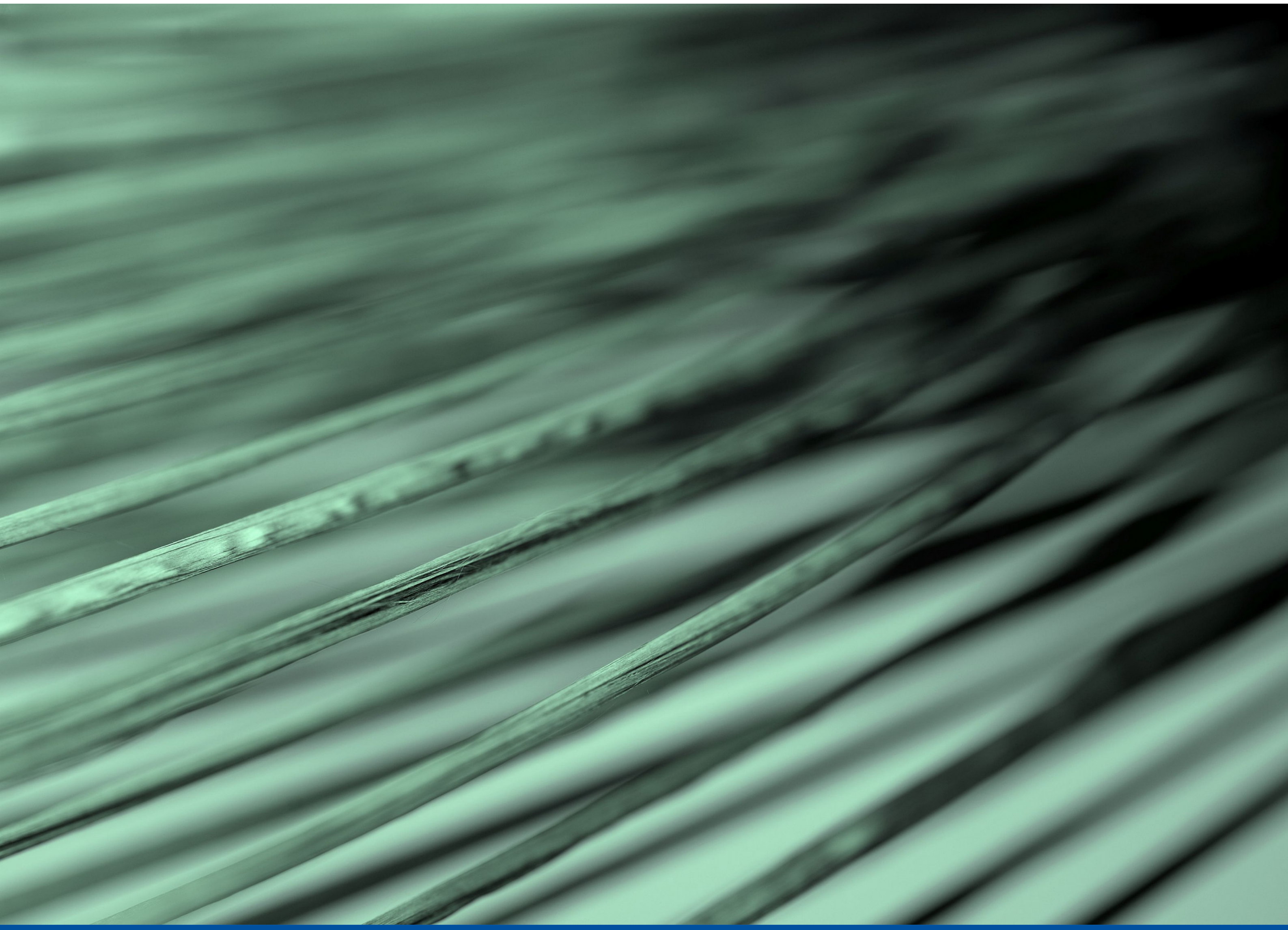

Recommendations for resource efficient and environmentally responsible manufacturing of CFRP products

Results of the Research Study MAI Enviro 2.0

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Foreword

Prevailing, ever more urgent challenges, such as climate change, raw material shortages, energy transition and an ageing population are developments which politics, industry and society must tackle together. Germany's Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF) supports such cooperation with research funding to help create solutions, find answers and facilitate innovation. The networking of players can, in particular, generate new momentum and enable synergies. In order to strengthen regional innovation potential, the "Leading-Edge Cluster Competition" (Spitzencluster-Wettbewerb) was initiated within the framework of the German Government's "High-Tech Strategy". With partners from the Munich-Augsburg-Ingolstadt (MAI) region, the MAI Carbon Cluster has been able to establish itself as a competence centre for fibre composite technologies over the course of five years.

Research projects along the entire value chain of carbon fibre-reinforced plastics (CFRP) contributed significantly towards making CFRP technology viable for use in large industrial series production. In addition to the reduction of manufacturing and processing costs, the consideration of efficiency and sustainability of fibre composite technology were key priorities of the MAI Carbon Leading-Edge Cluster, in line with the overall concept of sustainable technology development.

The implementation of high-tech applications with sustainable materials is gaining increasing significance. The use of CFRP has only been established in some areas to date, however, partially because of the higher energy requirements for the manufacture of CFRP structures compared to comparative metallic components. Also, as the use of so-called "recycled fibres" has also not yet been established, CFRP cannot be presently described as being sustainable.

In order to fully utilise the potential of the material and at the same time improve the quality of life for us all without inducing further negative ecological or social consequences, it was important for us to investigate the sustainability aspects of CFRP technology in addition to its light-weight construction capabilities within the framework of the MAI Carbon Cluster. Until now, no detailed data concerning the material's sustainability and life cycle aspects have been available so this provided the impetus for the evaluation of the eco- and cost-efficiencies of CFRP structures in the two collaborative projects "MAI Enviro" and "MAI Enviro 2.0". Starting from the analysis of various manufacturing processes, both research projects have compiled parametrisable data for environmental life cycle assessment which can thus be used for the assessment of technology development. These form the fundamental basis for recommendations for the course of actions for the optimisation of CFRP processing and the entire value chain with respect to resource efficiency and sustainability.

These works demonstrate that BMBF funding in the field of materials research can create the conditions necessary for sustainable product and process innovations for industry and society.

Liane Horst

Liane Horst

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Foreword

Carbon fiber reinforced plastics (CFRP) provide a lot of opportunities for industry. Besides high strength and stiffness at a low weight, properties like corrosion resistance or a good fatigue behavior are often important for products, too. Companies from various sectors work on concepts, as well as specific CFRP products and components, for a broad variety of applications. Critical success factors, especially for the automotive industry, are production costs and life cycle environmental impacts. Both are linked to technical parameters, such as cycle times of individual production processes.

Regarding production times and costs significant improvements have been achieved in the last years. Especially within the scope of the leading-edge cluster MAI Carbon the cycle time and the production costs could be reduced dramatically. Different projects and processes have proven that a cycle time of under 90 sec is realistic for thermoplastic parts. Also thermoset systems have increased the speed enormously. At the same time costs could be reduced significantly. This technological progress leads to a higher usage of carbon composites in the automotive industry and the mechanical engineering to profit from the mechanical performance of the material.

Despite the positive developments mentioned before, the question of sustainability has to be discussed and the effect of carbon composites on the life cycle assessment of products should be evaluated. The leading-edge cluster MAI Carbon initiated two projects, MAI Enviro and MAI Enviro 2.0, to create a valuable foundation for this work. Both projects examine different production processes and create data sets about these processes. This does not only create the basis for a well-founded evaluation of the life cycle assessment of products, but also shows the positive effect of the latest developments to the energy consumption for the production of CFRP parts. MAI Enviro 2.0 goes one step further and made a calculation for combustion driven cars.

So not only in the field of production processes the essential conditions for the usage of CFRP in different sectors was created, but also the requirements for a sound LCA are given now.

Prof. Klaus Drechsler

Acknowledgement

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Audi AG, BASF SE, Benteler SGL, bifa Umweltinstitut, BMW Group, CarboNXT, CG TEC, Compositence, Daimler AG, KraussMaffei, Munich Composites, SGL Group, Toho Tenax Europe.

Content

1 Introduction

MAI Carbon is one of the fifteen leading-edge clusters, funded since 2012 by the Federal Ministry for Education and Research (BMBF) and supervised by the project management Jülich (PTJ). MAI Carbon brings together partners from the cluster region Munich (M), Augsburg (A) and Ingolstadt (I). Main objective of the leading-edge cluster is to enhance the technology readiness level of CFRPs for high volume applications, establishing a strong SME environment and social marketing in Germany. This requires leap innovations throughout the life cycle of a structure, beginning with the fiber and matrix material through manufacturing of components and product systems to coherent recycling approaches. In addition, the research activities in MAI Carbon shall lead to significant reductions regarding the production costs and environmental burden (see Table 1).

Wherever masses are required to be moved the excellent weight-specific performance of CFRP results in energy, fuel and emission savings during the use phase of a product. Next to economic challenges due to the high material costs and low automation degree of process chains, the sustainability benefits of these materials significantly depend on the manufacturing chain, the achieved weight reduction and the respective application. Studies indicate, however, that under certain conditions a reduction of the environmental impact compared to metal structures are possible over the entire life cycle of a CFRP structure [1-8]. Missing databases and diversity of available manufacturing technologies have hampered reliable investigations so far.

Motivation for this is study is on the one hand to quantify the economic and environmental benefits achieved by the leap innovations developed in the framework of MAI Carbon. On the other hand, relevant production parameters are identified, an impact on the energy, environmental and cost efficiency of a process chain. This includes energy efficiency analyses of various processes but also investigations of State of the Art (SotA) and innovative process chains regarding their energy efficiency and environmental impact for different production setups. Furthermore, the influence of technological improvements and production related boundary conditions on the weight-specific costs and environmental footprint of a CFRP structure was systematically analyzed. Thus, the presented results serve as guideline for resource-efficient production of CFRP components. In this regard goal of this study is not to analyze specific products. Even though for energy data acquisition different part complexities are considered, general assumptions for the material flow, finishing and assembly are made. Also impacts on the complete design of a (hybrid) product system, is neglected. Thus, this study illustrates only possible indicators for an economic and environmental improvement. For a specific product a separate evaluation has to be done and the results may differ.

Table 1: Strategic objectives of the MAI Carbon Cluster

Strategic objectives	Definition	Target values
Cycle time	The time required to complete one cycle of a plant production program from start to finish for a single process step	< 1 minute
Reduction of process costs	Share of production costs per unit costs of one component in series production	- 90%
Efficiency during production processes	Reduction of the number of process steps	+ 60%
Reduction of waste in production process	The proportion of material waste in kg measured by CC-material used in total during the production process	- 50%
Recycling rate	Used material, which can be recycled after its end of life	80%
CO_2 efficiency	CO_2 equivalents will be compared with one another	A positive CO_2 balance

2 Guideline

This study is divided into six main chapters amended by general information.

Approach and evaluation methods
To perform a reliable economic and environmental evaluation, a large amount of input variables is necessary. Thus, the approach for data acquisition is described in this chapter. In addition, the applied methods used to evaluate the energy efficiency, the environmental impact and the weight-specific costs are explained from **page 8.**

Process energy efficiency
In this chapter the weight-specific process energy demands of more than ten processes are investigated. Each technology and typical applications are described briefly. The process window is given including all varied parameters, and the impact on the weight-specific process energy demand is illustrated. Each process is presented on one **page 16 to 27.**

Environmental impact of CFRP process chains
Based on the process energy efficiency the impact of different production setups on various process chains is analyzed in chapter 5.
For each process chain a short description is given. Then the results of the energy analysis are presented. This includes the illustration of main consumers as well as the identification of the most relevant production parameters for the weight-specific process energy demand. Based on the results possible optimization potentials are summarized. As the required material has a significant impact on the total process energy demand and on the environmental footprint of the process chain, the material flow is illustrated and discussed as well. To keep it simple, no additional trimming process is presented in the material flows. The cut-offs are directly considered in the previous process step. In addition to the weight-specific process energy demand, the environmental footprint incorporating three impact categories (non-renewable primary energy demand PED, fossil abiotic resource depletion potential ADP and global warming potential GWP) are investigated. Furthermore, the share of carbon fiber production and processing technologies on the total environmental footprint is discussed. Each process chain is presented on two pages from **page 28 to 48.**

Impact of production related measures on the environment
In chapter 6, starting on **page 50**, the environmental impact of different material-efficient process chains for the production of a thermoset and a thermoplastic based CFRP structure are analyzed. As base cases a NCF-RTM process chain and an organosheet production with an average cut-off of 40% was chosen (SotA in 2012). The evaluated differences regarding the PED, ADP and GWP are discussed in detail. Besides that, the impact of different production setups for thermoset and thermoplastic based CFRPs, such as the fiber volume content as well as the part size and thickness on the environmental burden is presented for the respective base case. Finally, possible optimization potentials are explained, including process energy, technology and design measures, and the environmental impact is discussed in detail.

Impact of production related measures on the product costs
The cost analysis includes the evaluation of three different thermoset based CFRP process chains. Next to the SotA NCF-RTM process chain, a material-efficient layup technology for curved parts is considered. For profiles, the braiding technology is analyzed. The weight-specific production costs are evaluated and discussed on the one hand for different part geometries, sizes and FVC. On the other hand, the impact of material price reductions and technology measures are investigated.

Summary
In the end all relevant results are summarized and compared with the strategic objectives of the MAI Carbon Cluster.

3 Approach and evaluation methods

In general, the analysis presented in this study addresses sensitivities of various production scenarios and part geometries as well as the inherent capacities of reduction. It does not reflect the energy efficiency, the environmental impact and the costs of a specific CFRP structure.

The quality and reliability of a life cycle assessment and economic viability analysis strongly depend on the underlying data. For well-established materials, high quality data sets are available to track the environmental interactions across the life cycle of a product (provided e. g. by PlasticsEurope, International Iron and Steel Institute IISI). Looking at the manufacturing of high-performance composite structures, however, only few data sets exist. In addition, it is often not clear, which production parameters and boundary conditions these data sets are based and under which conditions they are valid. Thus, for this study a comprehensive data collection was performed before different CFRP process chains and production parameters were evaluated regarding the environmental and economic impact.

3.1 Energy analysis

Goals of the process specific energy measurements are to determine all relevant life cycle inventory data for different CFRP process chains, as well as to develop empirical models, allowing energy demand estimations for different production setups. Measurements were done with varying part complexities and process parameters. The energy data were gained through different power meter devices: The Fluke 1730, Fluke 435 and the CML 1000, depending on the rated current. Compressed air was measured with a paddle-wheel sensor from Höntzsch. For the conversion of compressed air consumption into the required energy demand, the GaBi life cycle inventory data for a compressor with medium electricity consumption [9] were adopted. The general procedure for evaluating the energy efficiency is shown in Figure 1.

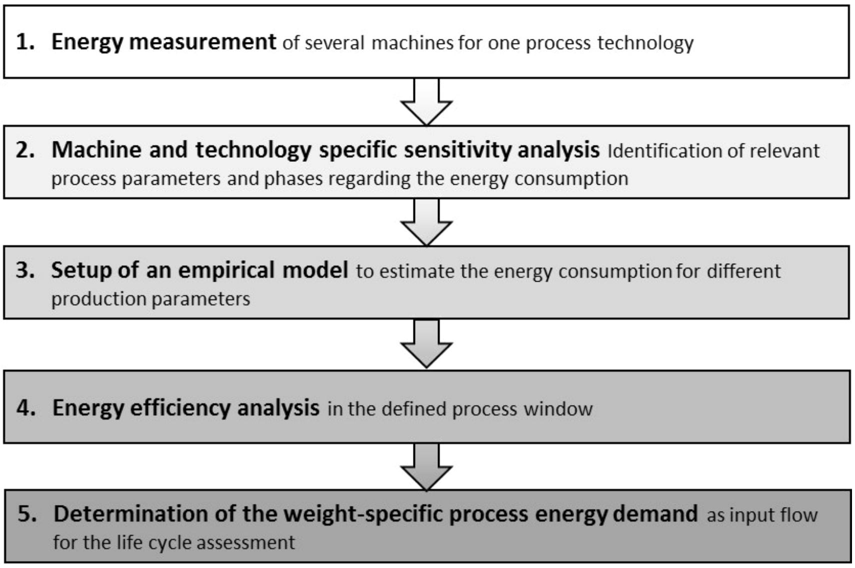


Figure 1: Approach and workflow of the energy efficiency analysis

In the first step, relevant process parameters, the possible process window and the resulting experimental setup were defined. Due to the number of possible parameter combinations, the number of trials was limited to the most relevant setups. The energy flows were measured in unloaded conditions. Furthermore, all data were tracked for the manufacturing of different part complexities. An overview of all measured production scenarios for each technology can be found in the appendix C.1.

Based on the results for each process phase (e. g. heating up the tool), equipment and machine type, a sensitivity analysis was performed. Necessary phases and parameters were then considered in the empirical model. For validation, the energy consumption estimated with the empirical model was compared with the measured energy amount required for manufacturing parts of various complexities. A maximum deviation of 10% was determined across the various technologies.

The energy flows used in the life cycle assessment relate to a defined mass, so the relation of the produced mass and the required energy has to be considered. For example, smaller components usually result in lower layup rates for placement technologies due to the braking and acceleration times. The weight-specific energy consumption is therefore lower for larger components. For modelling an IR heater, it is assumed that the process time does not depend on the part thickness in the considered process window (part thickness 1 mm to 3 mm). Also, the heater size is fixed to a certain value, independent from the part size. Thus, a larger and thicker preform/part results in a lower weight-specific energy demand. Looking at forming and curing technologies, smaller components usually require presses with lower nominal closing forces and smaller self-heated tooling, which lead to a lower energy consumption. However, the energy reduction is not proportional to the weight reduction, so the weight-specific process energy demand varies with the part size. Furthermore, it is assumed that forming a thicker preform or thermoplastic sheet does not result in longer process times and higher energy consumption. Thus, the weight-specific energy demand decreases with thicker components. For the infiltration of thicker parts, a longer injection time is considered. The total curing time is assumed not to change.

All the mentioned aspects are considered in the empirical models, which serve to determine the weight-specific process energy demand related to the respective semi-finished product (produced with the corresponding process technology). For example, the models estimate the energy consumption for the DFP process per kg placed preform and for the RTM process per kg CFRP. The development of the empirical models based on the measured data is explained in detail in [10].

The results of the energy analysis per manufacturing technique can be found in chapter 4. All variable parameters in the empirical model are varied within the defined process window and the respective energy consumption is calculated. To ensure an efficient analysis, only one factor at a time (OFAT) is changed, while the others remain on the medium setup. Here a positive percentage change equals an increased energy demand compared to the base line, whereas a negative one shows the possible reduction potential. However the OFAT analysis does not consider interactions between specific parameters. The maximum fluctuation of the process energy demand within the defined process window is determined through the empirical model by combining all parameters leading to a decrease or to an increase of the process energy demand, respectively.

To estimate the process energy demand for a complete process chain in chapter 5, the material flows are considered as well. However, cut-offs during textile production and materials remaining on the spools are neglected in this study. In total more than 20 parameters for each process chain are varied within a defined process window for the energy analysis. Again, only one factor at a time (OFAT) is changed, while the others remain on the medium setup. The maximum fluctuation of the process energy demand within the defined process window is determined through the empirical models by combining all parameters leading to a decrease or increase of the process energy demand, respectively.

3.2 Life cycle assessment to evaluate the environmental impacts

To quantify the resource consumption and the environmental impacts of processes, products and services, the method of life cycle assessment (LCA) according to DIN EN ISO 14040 and DIN EN ISO 14044 is often applied. Considering the life cycle point-of-view, LCA aims taking into consideration all relevant used resources, all relevant released emissions, and all related environmental impacts over the entire life cycle of a product, beginning with the provision of raw materials through manufacturing and application (use phase) to recycling or disposal at the end of life. A LCA study is broken down into four phases, conforming to the ISO standards [11]. Three of the four phases – the definition of goal and scope, the life cycle inventory, and the life cycle impact assessment – are described in the following. Detailed case-specific description, as well as the interpretation and discussion of the results are presented in chapters 5 and 6.

Goal and scope

The first phase includes the specification of all relevant boundary conditions for the analysis, as well as the functional unit to which all results refer. Focus of this study is to identify the main influences on the process energy demand and on the environmental indicators for the production of 1 kg CFRP as well as the impact of an optimized part design. The end of life is not part of this study. Furthermore, the functional unit is related to a defined mass, i.e. any possible impact on the performance due to a different production setup is not considered. An exception is the evaluation of a load-path adapted design. Here different lightweight potentials referring to a certain baseline are investigated. Besides that, the transportation of the carbon fibers and intermediate products are not considered in the balance. The LCA was performed using the GaBi ts software version 8.1.0.29, database version 8.6 SP33 [12]. For the life cycle impact assessment, the CML method by the University of Leiden was selected.

Life cycle inventory

The life cycle inventory (LCI) contains all material and energy flows required to provide the functional unit in the defined technical systems. In the resulting mass and energy balance (life cycle inventory results) all resource extractions from the environment are listed at the input side. The occurring emissions to air, water and ground are at the output side. For the data provision the model can be divided into a technical foreground and background system, see Figure 2.

While material and energy flows in the foreground system are usually defined through intermediate products, e. g. the amount of electricity or resin demand, the background system links those data with the corresponding resources taken from the environment and resources released to the environment [13].

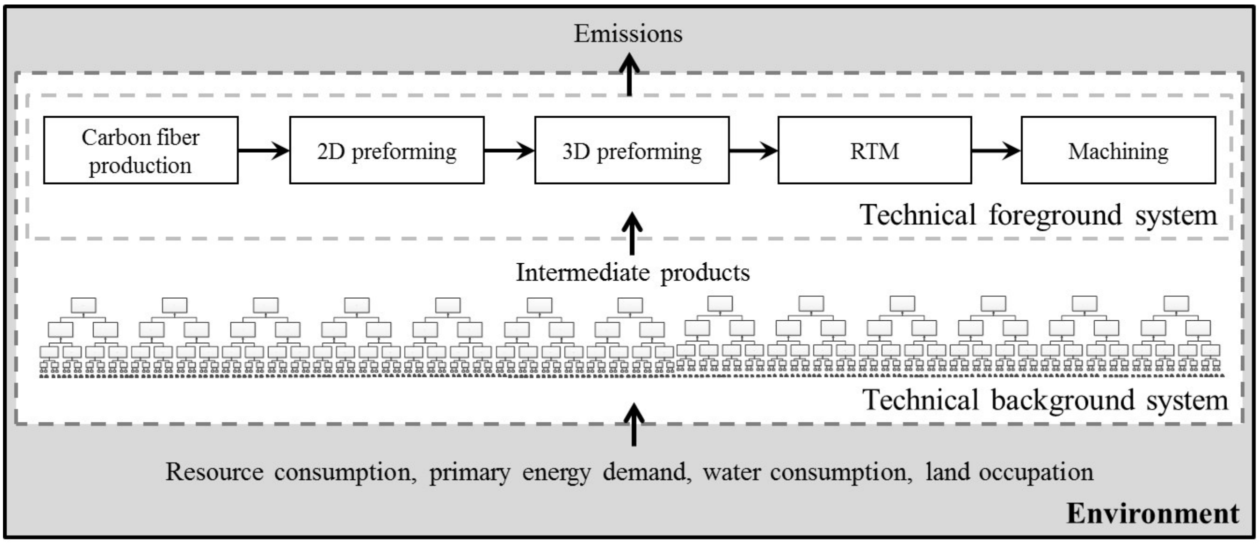


Figure 2: Technical fore- and background of a product system [13]

For all background data (energy supply, PAN fiber production, and epoxy resin) the GaBi Professional database is used.

For the foreground system, industry data provided by the advisory board comprising AUDI, BASF, Benteler-SGL, BMW, CarboNXT, SGL Group and TohoTenax are taken, amended by literature data. This particularly includes the carbon fiber and textile (fabric, NCF) production as well as the finishing. Reliable data for different preforming, curing and thermoforming technologies are hardly available. In addition, the corresponding production scenarios are often not documented. These values were gained through the energy analysis. An exception is the data set for recycling, which is associated with high uncertainties. The published energy requirements and emissions arising from the pyrolysis process could neither be validated nor be corroborated by the advisory board. In order to allow a comparison between the recycled fiber and the virgin fiber, differences in quality between the recycled and the virgin fiber were taken into account by means of value corrections. Value correction is a method commonly used in life cycle assessment. For example, economic data corrections are often carried out for secondary metals, meaning that depreciation of the secondary material values compared to the primary material values is taken into account by allocating credits with regard to avoided primary production. Details on credits and value corrections in the life cycle assessment can be found in Hohmann et al. [10].

In addition to the energy and compressed air demand, the cooling water consumption was measured for all relevant processes. The consumption of cooling water, as far as the flow was actively controlled, was recorded through ultrasound using the KATflow230. In all other cases, the water consumption was estimated using the Bernoulli equation based on the pressure loss of the main supply pipeline between input and output, the pipe diameter, and the process time. Since the cooling system is a closed-loop, an estimated loss of 5% is factored in all measured or calculated volumes, representing leakage and evaporation. Possible emissions as well as particulate matter occurring within the preforming, curing and finishing steps were neglected.

To represent the broad variety of cases, a parameterized material and energy flow model was developed using the LCA software GaBi 8 on the basis of the life cycle inventory data. The model allows the efficient environmental analysis of the production of CFRP structures. The central parameter control embedded in the model enables specific variations of processes, process chains and production boundary conditions in designated scenarios. Central parameters, including their interdependencies in the process chain, were identified and consistently represented in the model. Thus, mass and energy balances of CFRP structures could be created for a variety of cases, scenarios and variants that depict different process configurations and production chains. These serve as the basis for the detailed evaluation of various environmental metrics.

Life cycle impact assessment of the production phase
Based on the primary and literature data, material and energy flow balances of the technical system are compiled (the life cycle inventory). From these balances, three sustainability metrics are calculated: global warming potential GWP, fossil primary energy demand PED, and abiotic depletion potential ADP.

All results are scaled to 1 kg mass of the finished CFRP part. The environmental indicators are quantified in the following units:

- Primary energy demand, non-renewable:
  MJ per 1 kg CFRP part
- Abiotic resource depletion potential, fossil:
  MJ per 1 kg CFRP part
- Global warming potential:
  kg CO2 equivalent per 1 kg CFRP part

Evaluation of the use phase
In addition to the life cycle impact assessment of the production phase of different CFRP process chains and the investigation of the impact of energy and technology related optimization measures, the reduction potential of an optimal part design is analyzed. In this regard, savings can be achieved in the production phase as less material for the same function is required but also in the use phase. Weight reductions usually result in fuel savings considering conventional combustion engines.

To quantify the saving potentials following assumptions have to be applied:

- Potential weight savings
- Driving performance
- Fuel savings due to the achieved weight reduction

However, in this study only a conventional CFRP design and a fiber optimized design are compared to address the environmental impact of improved design methods. A comparison with other lightweight materials as well as the investigation of the end-of-life phase is out of scope. Furthermore, the focus of this investigation is to identify optimization potentials rather than to evaluate specific CFRP structures. Therefore, as baseline 1 kg CFRP is chosen. A better material understanding, further developments in design software and new processing technologies can result in an optimized part design in the near future. The following assumptions for possible **weight savings** were made (according to the results of MAI Carbon):

- 0% weight reduction
  - Isotropic loads, conventional design and SotA preforming technologies
- 10% weight reduction
  - Isotropic loads, optimal design and SotA preforming technologies
  - Anisotropic loads, conventional design and SotA preforming technologies
- 20% weight reduction
  - Anisotropic loads, optimal design and SotA preforming technologies
- 30% weight reduction
  - Anisotropic loads, optimal part design and a preform technology allowing a load path adapted fiber placement

The **driving performance** is kept variable in this study. However, for a detailed analysis, the distance is fixed to 200,000 km in some figures. For the **fuel production and supply** GaBi datasets for premium grade gasoline and diesel [14] are used.

Weight reductions are one of the most important measures to reduce the fuel consumption of automobiles. For the estimation usually, a **fuel reduction value (FRV)** is used, which describes the fuel reductions per 100 km driving performance and 100 kg saved weight. The achievable FRV depends mainly on following parameters:

- Type of power supply (gasoline, diesel, electricity, gas)
- Vehicle mass
- Engine power rating
- Technical configuration (e. g. manual or automatic, four-wheel drive)
- Driving conditions (traffic situation, ambient temperature, etc.)
- Air and rolling resistance of the vehicle
- Behavior of the driver

For gasoline and diesel combustion engines FRVs can be found in the literature both for the new European driving cycle (NEDC) and for the worldwide harmonized light vehicles test cycle (WLTC). The documented FRVs as well as the used ones for this study are summarized in Table 2. For gasoline engines a FRV of up to 0.15 l per 100 km driving distances and 100 kg weight savings can be reached. For diesel engines up to 0.12 l are possible. If primary weight reductions of more than 100 kg are feasible, higher FRVs can be achieved due to secondary measures, e.g. adaption of the powertrain [15].

However, these values are only valid for combustion engines. With the increasing electrification of the power supply, the FRVs due to weight savings are decreasing. Thus, in this study only best-case scenarios are presented.

Table 2: Overview of published fuel reduction values [l per 100 km and 100 kg weight savings)

	NEDC [16-19]		**NEDC [20]**	**WLTC [20]**	**In this study**	
Type of fuel	gasoline	diesel	diesel	diesel	gasoline	diesel
Primary weight reductions	0.15	0.12	0.14 to 0.16	0.13 to 0.16	0.15	0.12
Primary and secondary weight reductions	0.35	0.28	0.23 to 0.26	0.20 to 0.23	0.35	0.28

3.3 Economic viability analysis to evaluate the production costs

A brief overview of various approaches of cost accounting is given, before the applied method is presented and discussed in detail. The results of the cost analysis can be found in chapter 7.

In this study production costs including material and manufacturing costs are investigated. This type of costs can be categorized into direct costs and overheads. Direct costs can be directly attributed to a product (e. g. material costs). Overheads are related to the operation of a business. Operating costs are traditionally calculated by means of a surcharge rate related to the direct costs. Concerning the manufacturing cost, a surcharge is given on top of the labor costs (compare Figure 3 left-hand side).

In highly automated factories, labor as part of direct costs represents only a minor portion. Mainly machine costs prevail, incurring very high rates of overheads. Using the same rates for processes with higher personnel requirements would automatically result in high manufacturing costs [21-23]. This does not often reflect the real situation. For a comparison of different manufacturing methods, an hourly rate calculation for machine costs is therefore often useful (compare Figure 3 right-hand side). For this purpose, all costs related to the machines are considered separately. Costs for staff (such as salaries and auxiliary wages) remain as direct manufacturing costs. The so-called residual manufacturing overheads, like rents for social rooms, are usually set against direct labor costs [21]. Another advantage of the hourly rate calculation for machines is that the costs for individual process steps can be described and analyzed separately, which enhances transparency.

In this study an hourly rate calculation for the manufacturing costs is applied. In the following sections a detailed explanation for each cost type as well as the underlying assumptions is given. This includes the calculation of the material costs (direct and overhead), the labor costs (direct and overhead) as well as the machine costs. For latter following aspects are considered:

- Imputed depreciation
- Imputed interest
- Rental costs
- Maintenance costs
- Energy costs

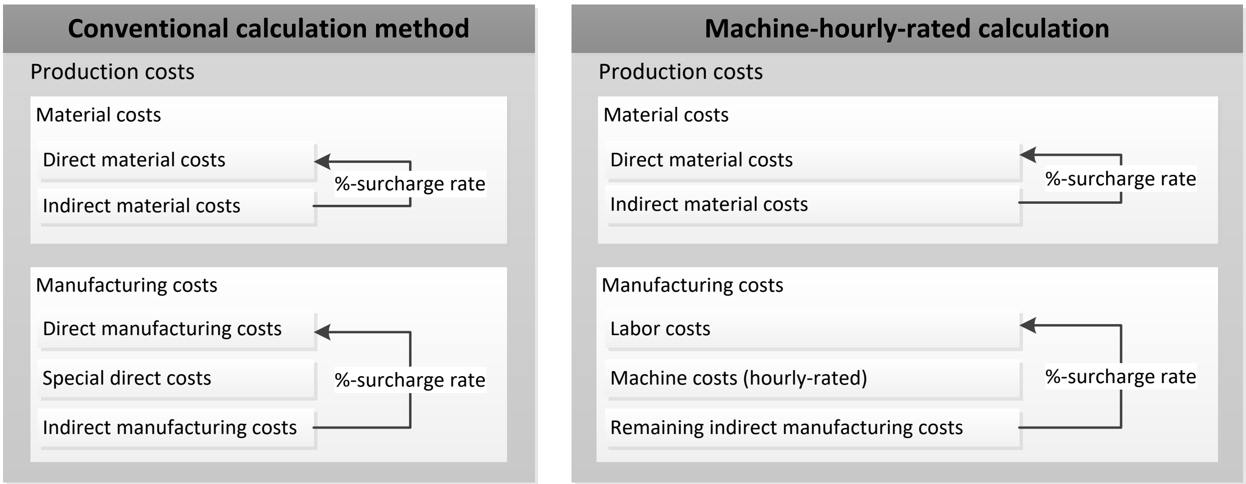


Figure 3: Comparison of different cost calculation methods according to [21]

3.3.1 Material costs

Material costs include costs for carbon fiber textiles (like bindered NCF and rovings), costs for resin system and partially required binder. Cores required for the braiding process are not considered in the material costs, as various kinds of material can be used partially with strongly diverting costs. All considered material costs are listed in Table 3. The label "high" represents the base case in 2012, "low" the cost target in 2020.

Table 3: Direct material costs

	High	Low
Bindered NCF	50 €/kg	25 €/kg
Roving	20 €/kg	10 €/kg
Binder	8 €/kg	1 €/kg
Matrix	6 €/kg	4 €/kg

Furthermore, it is assumed that the material costs are unaffected by order quantities and as a consequence are unaffected by the number of parts produced per year. The material prices as stated in Table 3 are taken for the cost analysis presented in chapter 7 and shall portray the full price range.

Some material costs may occur which can only indirectly be assigned to the part. This includes costs for example for purchase, storage and logistics [21,24]. By means of a material-overhead surcharge rate, these costs can be attributed to a specific part.

$$Indirect\ costs = direct\ costs * surcharge\ rate$$

In this study a constant surcharge rate of 3% is used for the calculation of the indirect costs.

3.3.2 Manufacturing costs

In terms of hourly rate calculation for machine costs, direct labor costs and a surcharge for the remaining manufacturing overheads are listed separately.

Labor cost / direct manufacturing costs

Labor costs arise in the first place for machine operators and vary according to the number of working shifts. The working hours are distributed to four shifts at hourly wages as stated in Table 4.

Table 4: Hourly wages for machine operators

1st shift	2nd shift	3rd shift	4th shift
40 €/h	40 €/h	60 €/h	65 €/h

The fourth shift, which includes night and holiday shifts as well as Sundays, is only permitted by German law under clearly defined conditions [25]. The three-shift schedule is therefore often the maximum of shifts being worked in Germany and was thus considered in this study.

The workforce needed to operate machines varies depending on the process step. It is assumed that there is no need for full workforce throughout the entire process time. The worker can thus be deployed to other tasks. Table 5 shows the percentage of the workforce needed for each machine. The remaining manufacturing overheads, including costs for example for the shop floor manager, are calculated by applying a certain surcharge rate in relation to the direct labor costs. For the following calculations a surcharge rate of 20% is considered.

Table 5: Required workforces

Process step	Required workforce*
Stacking of NCF	10%
Dry-Fiber-Placement	50%
Forming	10%
Braiding	50%
Resin-Transfer-Molding	10%
Machining	20%

*100% equals one operator for the total process time

Machine costs

Machine costs include e. g. costs arising from rental, interest rates, equipment depreciation and maintenance as well as energy consumption.

To determine the rental costs related to the machine, the required area including operating and maintenance space has to be determined and multiplied with a monthly rental price. In this study 6 €/m² was chosen.

Imputed interests are calculated with reference to the capital tied up in the respective equipment.

$$Interests = interest\ rate * 0.5 * loss\ in\ value$$

No residual value of the equipment at its end-of-life-performance is considered. The loss in value thus equals the acquisition costs. The interest rate is usually based on weighted cost of capital. Due to currently very low interest on debt capital, a rate of 3% is assumed.

The imputed depreciation is intended to show the actual depreciation of capital assets. Thus, not the acquisition costs but the replacement value at the replacement time of the machine is used as base value. This is aimed at the principle of capital maintenance as it has to be guaranteed that at the end of the operating life a new and probably more expensive machine could be purchased. The yearly depreciation costs were calculated considering a linear depreciation with consistent annual amounts.

$$Yearly\ depreciation = \frac{replacement\ value}{operation\ time}$$

The depreciation tables (related to one-shift operation) issued by the Federal Ministry of Finance can be used for a general orientation in order to determine the useful life of equipment. In this study, the altered operating life due to different utilizations was also considered. Here 75% of the given life time was fixed. A total utilization of the first shift results in the life time given in the depreciation tables. A lower utilization of the 1st shift leads to a longer use time and to lower yearly depreciation costs. In contrast a 2nd or 3rd shift decreases the operation time, resulting in higher yearly depreciation costs. Furthermore, it is assumed that the acquisition costs and the replacement value do not differ.

The maintenance costs are calculated using a percentage maintenance factor in relation to the replacement value of the machine. Again, it is assumed that there is no difference between acquisition costs and replacement value. For a fully utilized one-shift operation, a maintenance factor of 2.5% is presumed for all machines. Furthermore, the increased maintenance effort with a higher utilization is considered at hourly intervals. For example, a one-shift operation with a half-time utilization leads to 1.25%, a fully utilized two-shift operation results in 5% maintenance factor.

In the hourly rate for machine, the energy costs are also considered, which are determined through the energy analysis. The costs are gained through the multiplication with the energy cost factor. In this study, the calculations are performed with an energy cost factor of 0.1 €/kWh.

To get an hourly rate per machine, the determined final annual costs are allocated to the real production time per year. Here, unplanned machine downtimes and maintenance are considered, assuming a maximum machine availability of 85% for each process step. Due to the fixed annual costs (compare Table 6), the hourly rate per machine varies according to the utilization degree. As a result, a dynamic hourly rate per machine is calculated which relates to the utilization degree and thus enhances the transparency of the cost incurrence.

Table 6: Fixed and variable machine costs

<table>
<tr><th colspan="10">Machine costs</th></tr>
<tr><td colspan="2">Rental costs</td><td colspan="2">Interests</td><td colspan="2">Depreciation cost</td><td colspan="2">Maintenance costs</td><td colspan="2">Energy costs</td></tr>
<tr><td colspan="5">Fixed costs</td><td colspan="5">Variable costs</td></tr>
</table>

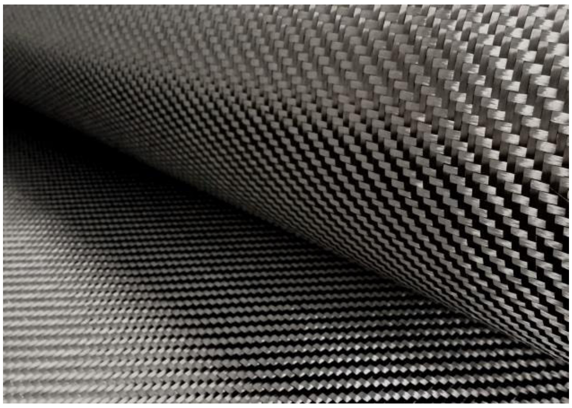
4 Process energy efficiency

Goals of the process specific energy measurements are to determine all relevant LCI data for different CFRP process chains, as well as to develop empirical models, allowing energy demand estimations for different production setups. Measurements were done with varying part complexities and process parameters. The energy data were gained through different power meter devices: The Fluke 1730, Fluke 435 and the CML 1000, depending on the rated current. Compressed air was measured with a paddle-wheel sensor from Höntzsch. For the conversion of compressed air consumption into the required energy demand, the GaBi LCI data for a compressor with medium electricity consumption is adopted [9]. An overview of all measured production scenarios for each process technology used in the investigated production chain can be found in the appendix C.1. The development of the empirical models based on the measured data is explained in detail [10]. The weight-specific process energy demand is related to the respective semi-finished product, which is produced with the corresponding process technology, i. e. for the DFP process the energy consumption per kilogram placed preform and for the RTM process the energy consumption per kilogram CFRP is determined. For the final energy analysis, more than 20 parameters are varied within a defined process window. Hereby only one factor at a time (OFAT) is changed, while the others remain on the medium setup. Thus, the OFAT analysis does not consider any interactions between specific parameters. Furthermore, the maximum fluctuation of the process energy demand within the defined process window is determined through the empirical model by combining all parameters leading to a decrease or increase of the process energy demand. A positive percentage change equals an increased energy demand compared to the base line, whereas a negative one shows the possible reduction potential. In this regard, these combinations are not representative for an industrial production setup because some parameters are inversely correlated. For example, higher curing temperatures usually results in shorter cycle times

4.1 Non-crimp-fabrics and fabrics

In the automotive industry, flat bindered textiles are commonly used for the production of cupped continuous reinforced CFRP parts. Several layers are tailored and stacked to a preform. The use of flat textiles leads to high productivity. But the restricted fiber orientation hardly allows load-path adapted designs, which results in a lower weight reduction than theoretically possible. Furthermore, cut-offs of up to 50%, depending on part size and textile roll, can occur, even though modern nesting programs can reduce the production waste.

Relevant data for the evaluation of energy efficiency and the environmental impact of the NCF and fabric production were gained through a literature survey. H. Stiller published the electricity consumption per square meter of textile production for glass and car-bon fibers in “Material Intensity of Advanced Compo-site Materials” [26].



4.2 Nonwovens

Mainly three different production routes for nonwovens are available – extrusion, wet-laid and dry-laid technologies. In this study the energy efficiency of wet-laid nonwovens is investigated. The fibers are separated in a pulper containing water and dispersing agent. The fiber suspension is further diluted and stored in a large vessel to ensure a continuous processing. The fiber suspension is subsequently distributed on a filter belt. The orientation of the nonwovens depends on the belt and distribution velocity. Excessed water is collected and used again until a critical number of additives is reached. Afterwards the nonwovens are dried step-wise through e.g. vacuum-assisted uhle boxes, convection ovens or IR heating systems. For the fixation a binder system can already be mixed into the fiber suspension or applied onto the nonwovens before drying.

Defined process window*

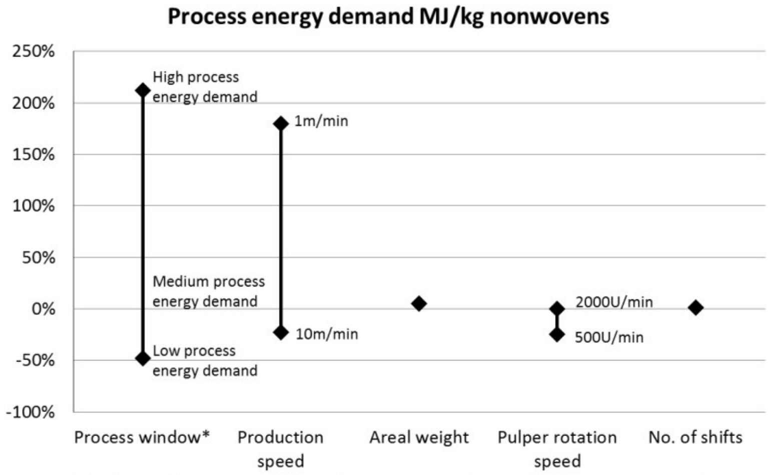
	Low	Medium	High	Unit
Production speed	10	5	1	m/min
Textile areal weight	250	200	150	g/m²
Pulper rotation speed	500	2000	200	1/min
No. of shifts per day	3	2	1	-

* Data were only measured for one lab-scale machine. Thus, the width of nonwovens is fixed to 0.31 m and the batch dispersion mass throughput for one pulp to 1.5 kg/h. The labeling of the production scenarios (low, medium, high) corresponds to the determined weight-specific process energy consumption.

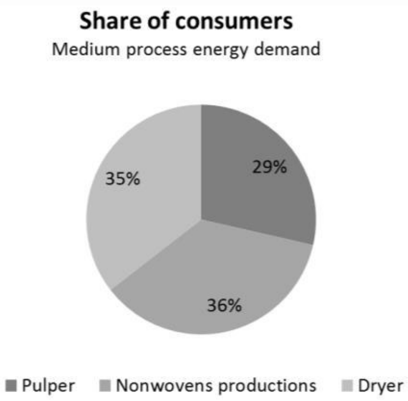
Results

In the defined process window the weight-specific energy demand varies between -50% and around 210%. As the baseline (0%) the medium production setup was chosen. The main influencing parameter is the production speed.

The energy consumption is divided relatively equal over the three main consumers pulper, nonwovens production and dryer for a medium production setup.



* Combining all parameters, which are leading to a low and to a high process energy demand



4.3 Tailored Fiber Placement

Tailored fiber placement (TFP) is a textile manufacturing technique based on the principle of stitching. The fibers are fixed with an upper and lower stitching thread on a base material. Glass or carbon (non-crimp) fabrics are used. In a subsequent step the preform is formed into the final 3D shape and infiltrated with resin. The roving type and the amount of simultaneously working stitching heads have a significant influence on the layup rates. Relevant process parameters and possible parameter values are shown in the table below.


IFB Uni Stuttgart

Defined process window*

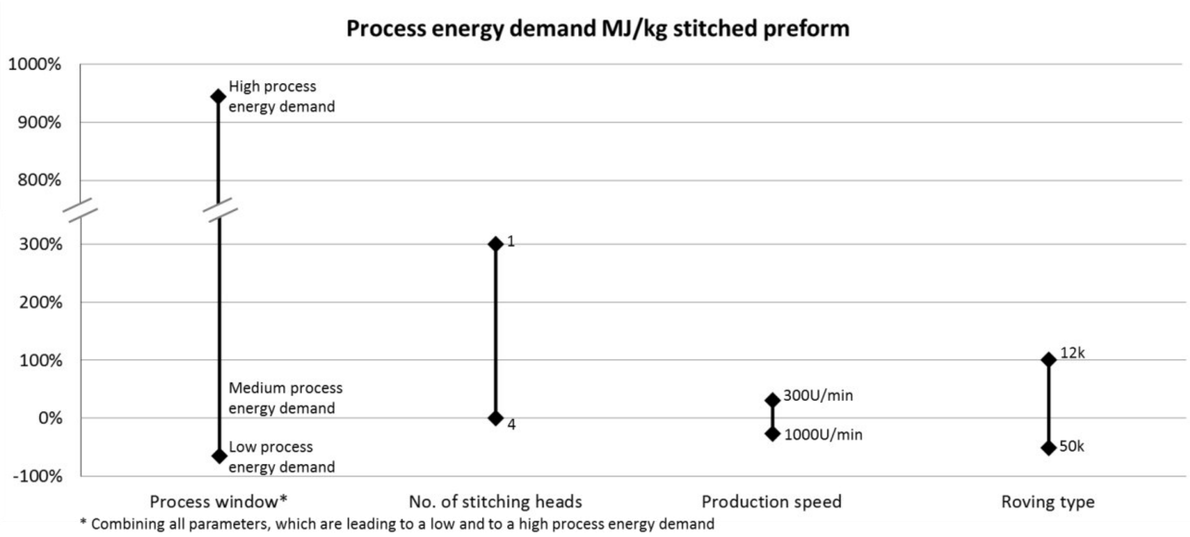
	Low	Medium	High	Unit
No. of stitching heads (parallel)	4	4	1	-
Production speed	1000	500	300	rpm
Roving type	50	24	12	k

*The labeling of the production scenarios (low, medium, high) corresponds to the determined weight-specific process energy consumption

Results

The investigated plant has in total four stitching heads. In an industrial setup usually more stitching heads are used. Thus the low and medium setup is fixed to the maximum number of the investigated plant. However in the defined process window the weight-specific energy demand varies between -64% and around +945%.

As the baseline (0%) the medium production setup was chosen. The main influencing parameters are the number of parallel stitching heads and the roving type. Even though a higher number of stitching heads results in an increased energy demand. The weight-specific energy demand is lower due to the increased productivity.


Process energy demand MJ/kg stitched preform

* Combining all parameters, which are leading to a low and to a high process energy demand

4.4 Dry Fiber Placement

The majority of currently available dry fiber placement (DFP) systems are robot-based. Depending on the equipment, a bindered/ stitched yarn or roving can be used. Each tow is fed and cut separately resulting in a near net-shape stack with cut-offs below 5%. Processible tow width differs from ¼ to 2 inches, with a simultaneous feeding of one to 16 tows. The fixation of the tows can be either realized through an activation of the binder (IR and laser) or the spread rovings are adhesively fixed at the edges of each course.

Compositence

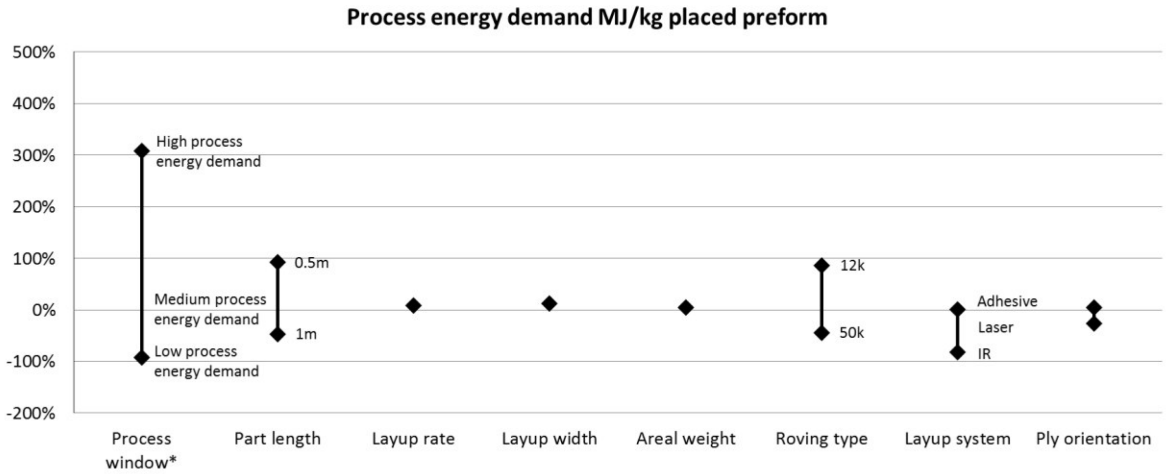
Defined process window*

	Low	Medium	High	Unit
Part length	1.5	1	0.5	m
Layup rate	50	25	10	kg/h
Layup width	300	200	100	mm
Areal weight	250	200	150	g/m²
Roving type	50	24	12	k
Layup system	IR	Adhesive	Laser	-
Ply orientation	0	30	60	deg

*The labeling of the production scenarios (low, medium, high) corresponds to the determined weight-specific process energy consumption.

Results

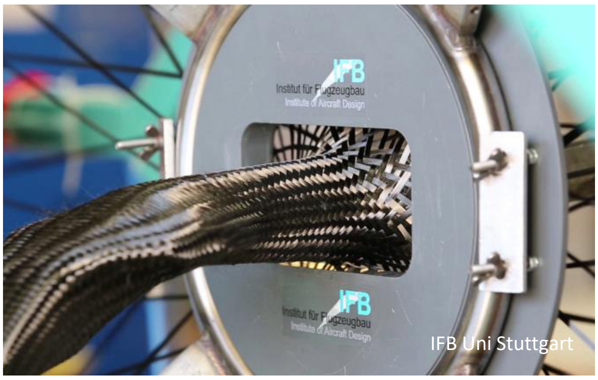
The weight-specific energy demand varies between -91% and +309%. The main influencing parameters are the part length, the roving type and the fixation system. The influence of the layup rate on the total process energy demand is marginal. The total process energy demand of the DFP process is dominated by the compressed air consumption with 65% to 85%. For adhesive fixation (medium production setup) the compressed air consumption does not depend on the process time but on the number of parallel-fed rovings. Hence, a higher layup rate leads to lower electrical energy demand per kilogram placed preform, while the dominating compressed air consumption remains unchanged.



* Combining all parameters, which are leading to a low and to a high process energy demand

4.5 Braiding

A braiding machine continuously weaves carbon fibers to a 3D-preform. The carbon fiber bobbins, which are placed on a (radial) braiding machine, move wave-like in opposite directions. Through the interlacing of the carbon fibers, a woven structure is realized on the mandrel, which is guided through the braiding machine by a robot system. The preform can be reinforced in 0° direction by additional filler yarns. When the carbon structure is fully woven, the tube is cut off, the mandrel retracts from the radial braider and another core takes its place on the machine. The rotation speed of the braiding machine is usually constant. Depending on the part complexity up to two additional robots are required for handling.


IFB Uni Stuttgart

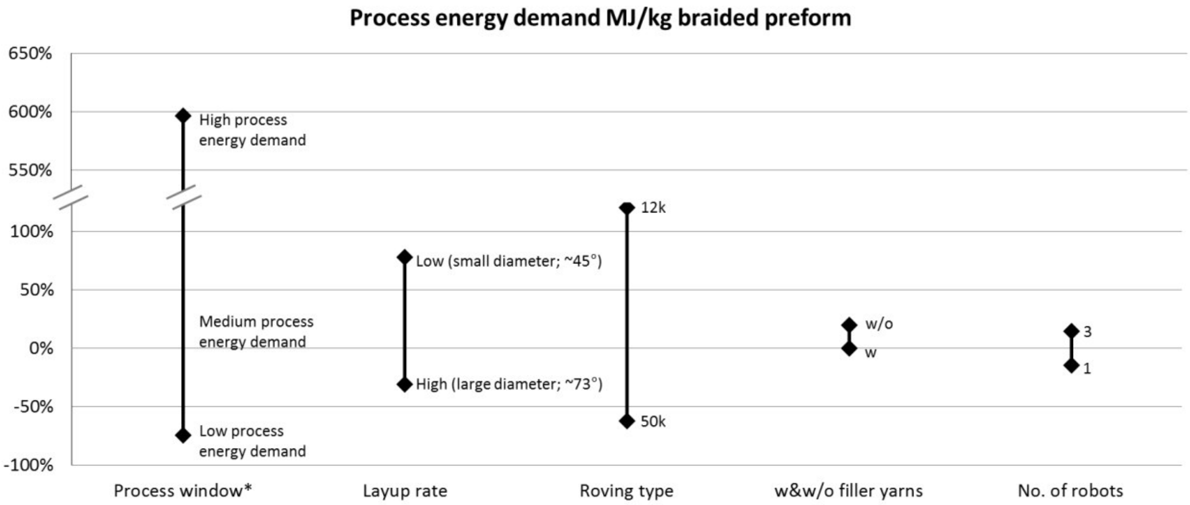
Defined process window*

	Low	Medium	High	Unit
Layup rate	~74 (50k) | ~ 33 (24k)	~23	~4 (12k) | ~13 (24k)	kg/h
Roving type	50	24	12	k
W and w/o filler yarns	with	with	without	-
Number of robots	1	2	3	-

*The labeling of the production scenarios corresponds to the determined weight-specific process energy consumption.

Results

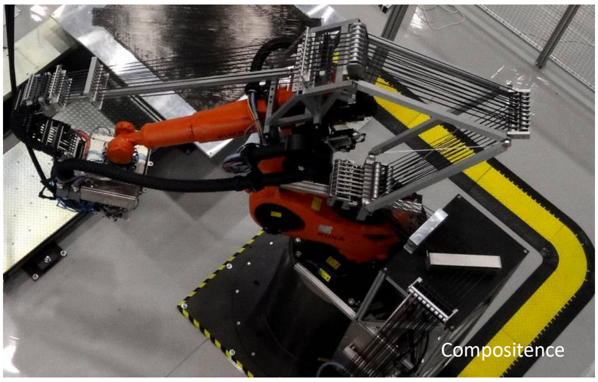
In the defined process window the weight specific energy demand varies between -74% and around +600%. As the baseline (0%) the medium production setup was chosen. The main influencing parameters are the roving type and the layup rate. The latter is defined by the required core diameter and fiber angle. The main energy consumption is caused by the braider, followed by the robots and the fiber extraction system.



* Combining all parameters, which are leading to a low and to a high process energy demand

4.6 Thermoplastic Fiber Placement

Thermoplastic fiber placement machines are mainly available as robot based layup heads. Each tow can be fed and cut separately resulting in a near net-shape stack with cut-offs below 5%. Processable tow width varies from ⅛ to 2 inches, with simultaneous feeding of one to 16 tows. For the fixation a laser is usually used as heat source. An alternative method is the application of an adhesive at the edges of each course. In general, there are two different processing chains available: Either the part laid-up in its 3D shape and consolidated in line or a 2D-/ 3D-stack is placed and then subsequently consolidated and formed.


Compositence

Defined process window*

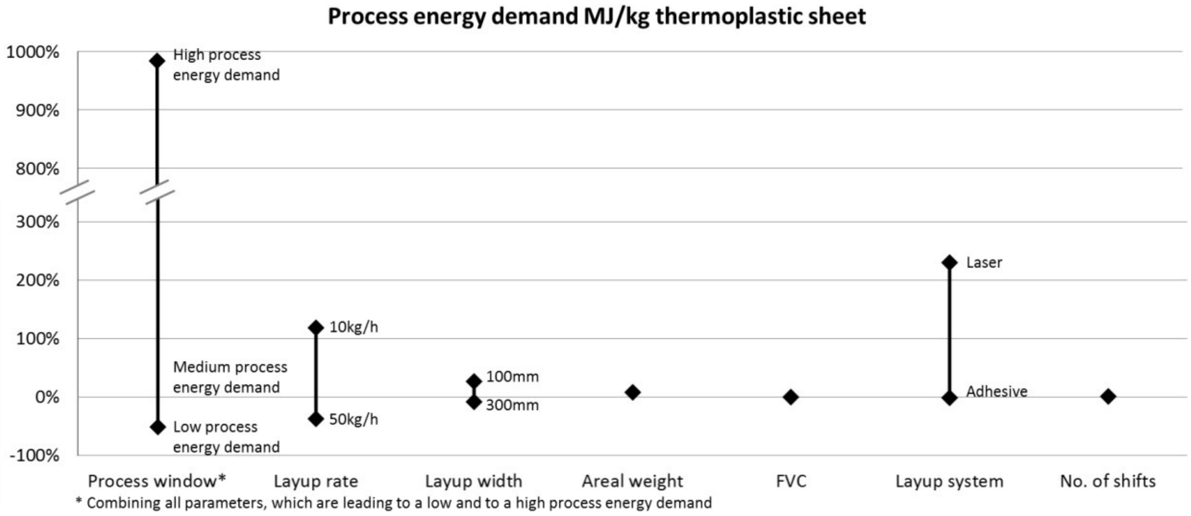
	Low	Medium	High	Unit
Layup rate	50	25	10	kg/h
Layup width	300	200	100	mm
Areal weight	250	200	150	g/m²
Fiber volume content (FVC)	55	50	45	%
Layup system	Adhesive	Adhesive	Laser	-
Number of shifts per day	3	2	1	-

*The labeling of the production scenarios (low, medium, high) corresponds to the determined weight-specific process energy consumption.

Results

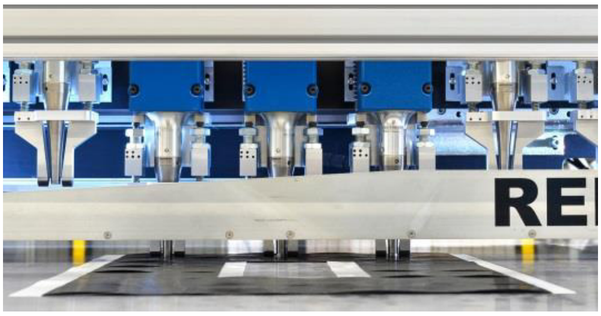
Focus of the investigation was a 2D layup process with a subsequent consolidation and forming step. In the defined process window, the weight-specific energy demand varies between -50% and around +1000%. As the baseline (0%) the medium production setup was chosen.

The main influencing parameters are the layup rate and the fixation system. In contrast to a dry-fiber-placement process, the adhesive fixation is the most energy efficient one. Still the main energy consumption is caused by the robot and the fixation.



4.7 Thermoplastic Tape Laying

Unidirectional reinforced thermoplastic tapes are laid-up on a moveable table. A gripper pulls the tape from the bobbin to the desired length, a cutter separates the tape from the bobbin and the material is placed on the table. Through the table movement, the angle and the linear position of the tape is adjusted. The first layer is fixed on the table through a suction fan; the following layers are selectively welded via ultrasonic welding.



Defined process window*

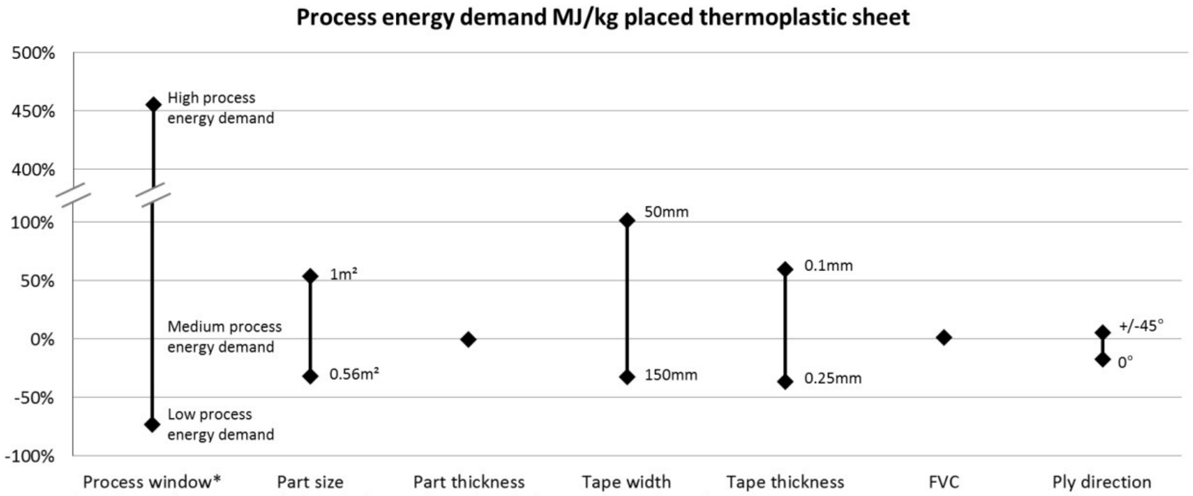
	Low	Medium	High	Unit
Part size	0.56	0.75	1	m²
Part thickness	1	2	3	mm
Tape width	150	100	50	mm
Tape thickness	0.25	0.16	0.1	mm
Fiber volume content (FVC)	55	50	45	%
Ply direction	0°	Quasi-isotropic	+/-45°	-

*The labeling of the production scenarios corresponds to the determined weight-specific process energy consumption.

Results

In the defined process window the weight-specific energy demand varies between -70% and around +450%. As the baseline (0%) the medium production setup was chosen. The main influencing parameters are the part size, the tape width and the tape thickness. Especially the part size has an impact on the required number of suction fans, fixating the first ply, which also dominates the energy consumption of the process.

Therefore for the production scenario resulting in a low process energy demand, the maximum part size possible with only one suction fan was chosen. For high process energy demand the minimum part size for four suction fans was considered. Besides that, smaller part sizes result in lower layup rates due to the acceleration and braking phases. The layup rate is also influenced by the tape width and the tape thickness.



* Combining all parameters, which are leading to a low and to a high process energy demand

4.8 Infrared heater

An infrared heater is usually required for heating up a bindered preform or an organosheet to its melting temperature before the stack is formed to its final 3D shape in a press. The investigations were limited to a heater temperature of around 250 °C. Therefore, the data are only valid for the activation of bindered preforms. Furthermore, it is assumed that the preform is continuously heated from both sides. For the evaluation of thermoplastic process chains requiring an infrared heater with higher temperatures, a data set in the GaBi database was available.

Defined process window*

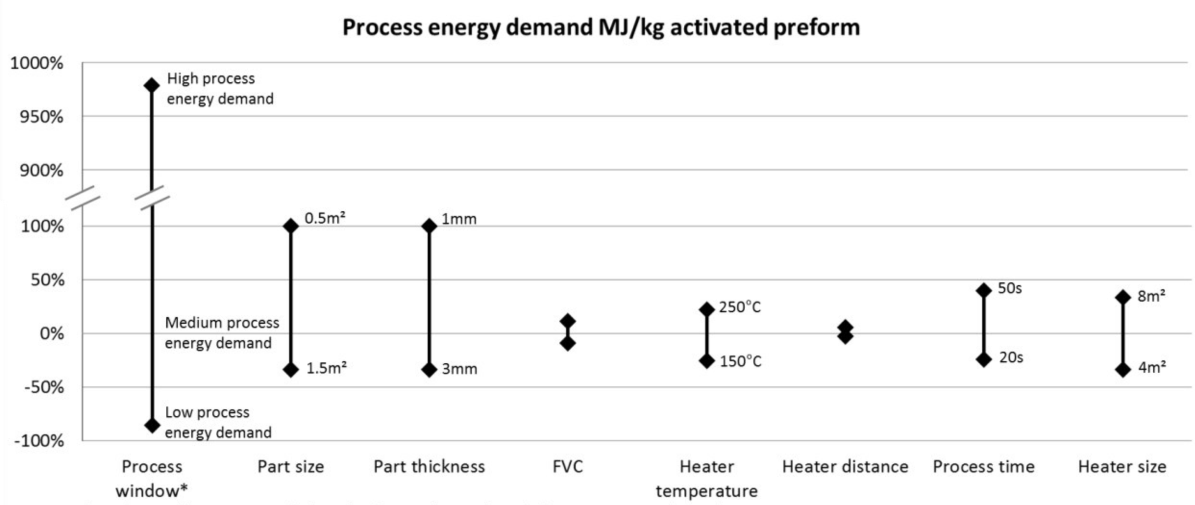
	Low	Medium	High	Unit
Part size	1.5	1	0.5	m²
Part thickness	3	2	1	mm
Fiber volume content	55	50	45	%
Heater temperature	150	200	250	°C
Heater distance to preform	80	100	150	mm
Process time	20	30	50	s
Heater size	4	6	8	m²

*The labeling of the production scenarios corresponds to the determined weight-specific process energy consumption.

Results

In the defined process window the weight-specific energy demand varies between -85% and around +980%. As the baseline (0 %) the medium production set- up was chosen. The main influencing parameter is the part geometry (size and thickness).

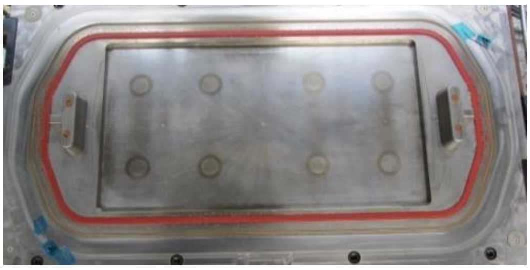
Assuming that the process time to reach the required temperature does not depend on the part geometry, large part geometries results in a lower weight-specific energy demand. Furthermore the heater temperature, process time and the heater size has an impact.


Process energy demand MJ/kg activated preform

* Combining all parameters, which are leading to a low and to a high process energy demand

4.9 Self-heated tooling

Self-heated toolings are usually used in manufacturing processes like resin transfer molding (RTM), wet compression molding (WCM) and forming of thermoplastic organosheets. For processing of thermosets, the heat is required to ensure cross-linking of the resin. For thermoplastic processing, a defined cooling of the preheated sheet, ensuring controlled crystallization, is realized. Water or oil can be used as heat transfer medium.



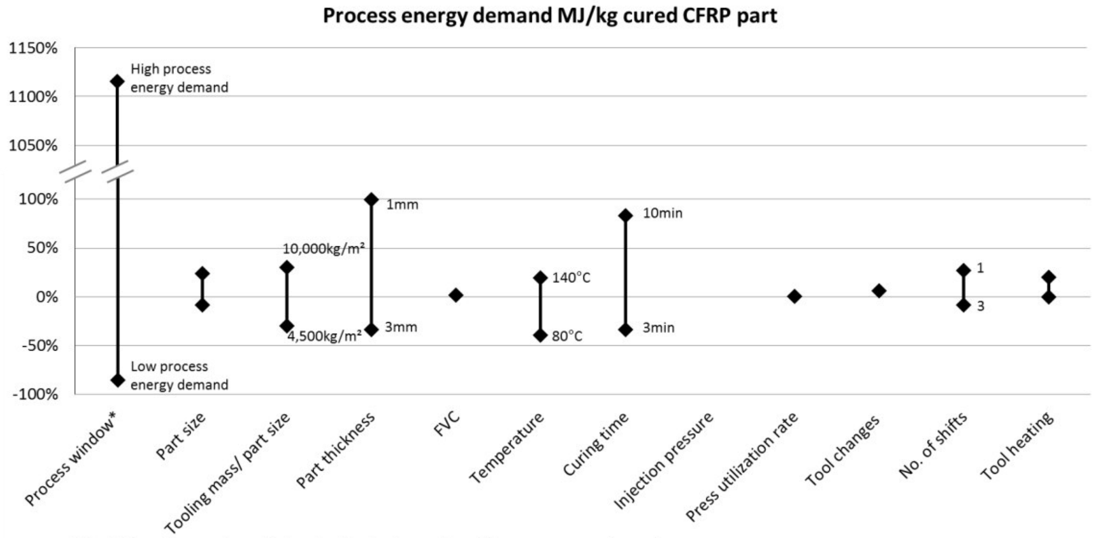
Defined process window*

	Low	Medium	High	Unit
Part size	1.5	1	0.5	m²
Ratio tooling mass / part size	~4,500	~7,000	~10,000	kg/m²
Part thickness	3	2	1	mm
Fiber volume content (FVC)	55	50	45	%
Tooling temperature	80	120	140	°C
Injection and curing time	3	5	10	min
Injection pressure	40	60	80	bar
Areal utilization rate of press	1	0.8	0.5	-
No. of tool changes per week	1	1	5	-
Number of shifts per day	3	2	1	-
Tool heating	Daily	Daily	Once a week	-

*The labeling of the production scenarios corresponds to the determined weight-specific process energy consumption.

Results

In the defined process window the weight-specific energy demand varies between -85% and around +1100%. As the baseline (0%) the medium production setup was chosen. The main influencing parameters are the part thickness, curing time, the ratio of the tooling mass to the part size and the temperature.



* Combining all parameters, which are leading to a low and to a high process energy demand

4.10 Hydraulic press

Carbon fiber reinforced plastics are commonly compacted, formed and cured under pressure. If the required temperature is realized through a separated heating device, e.g. self-heated tools, only the pressure has to be applied by the press. The hydraulic press is usually required for following process steps:

- Compaction and forming of dry preforms
- Applying clamping forces for RTM/ WCM
- Forming of carbon fiber reinforced thermoplastic sheets

Defined process window*

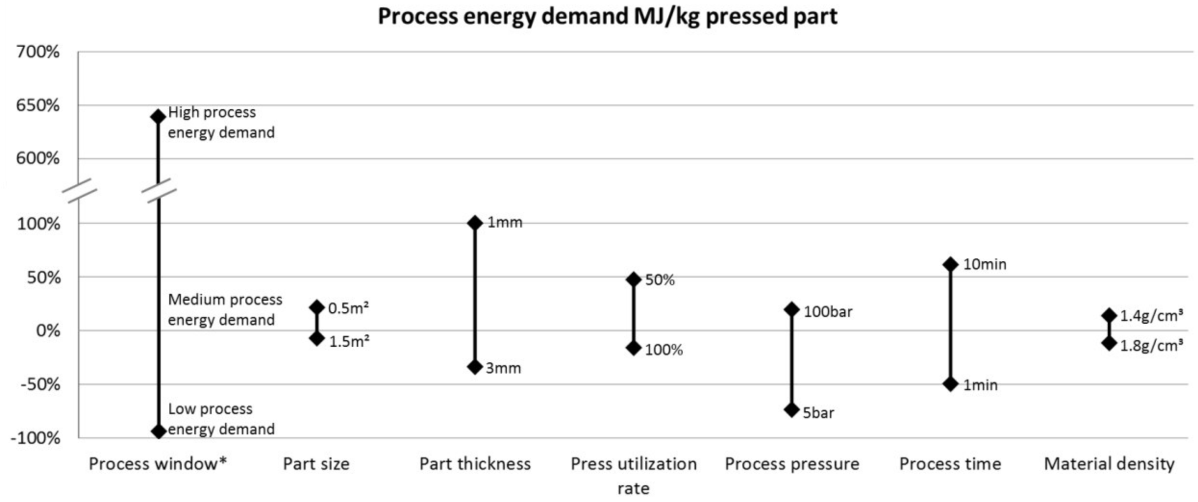
	Low	Medium	High	Unit
Part size	1.5	1.0	0.5	m²
Part thickness	3	2	1	mm
Areal utilization rate of press	1	0.8	0.5	-
Process pressure	5	80	100	bar
Process time (press closed)	1	5	10	min
Material density	1.8	1.6	1.4	g/cm³

*The labeling of the production scenarios corresponds to the determined weight-specific process energy consumption.

Results

In the defined process window the weight-specific energy demand varies between -93% and around +640%. As the baseline (0%) the medium production setup was chosen.

The main influencing parameters are the part thickness, the process pressure and the process time.


Process energy demand MJ/kg pressed part

* Combining all parameters, which are leading to a low and to a high process energy demand

4.11 Heating press

Heating presses are required for organosheet manufacturing and for the consolidation of selectively fixed thermoplastic sheets out of fiber reinforced thermoplastic tapes. Therefor a double-belt press or a continuous compression molding machine can be used with various isothermal temperature and pressure zones. In lab scale sometimes also variothermal heating presses are applied.

Defined process window*

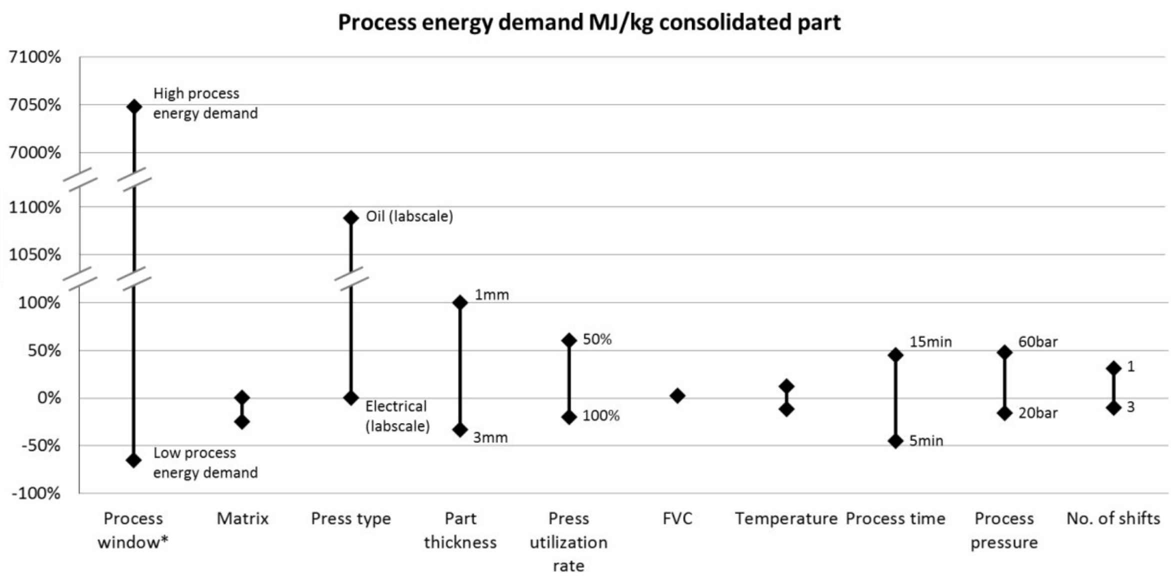
	Low	Medium	High	Unit
Matrix	PP	PA6	PA6	-
Press type	Electrical	Electrical	Oil	-
Part thickness	3	2	1	mm
Areal utilization rate of press	1	0.8	0.5	-
Fiber volume content (FVC)	55	50	45	%
Temperature zone 1 | 2	PP: 205 | 50; PA6: 260 | 60	PA6: 280 | 80	PA6: 300 | 100	°C
Process time for each zone	5	10	15	min
Process pressure zone 1 | 2	PP: 40bar; PA6: 1 | 20	PA6: 1 | 40	PA6: 1 | 60	bar
Number of shifts per day	3	2	1	-

*The data were obtained for different lab scale variothermal heating presses and then converted into a two zone heating press with isothermal temperatures. The labeling of the production scenarios corresponds to the determined weight-specific process energy consumption.

Results

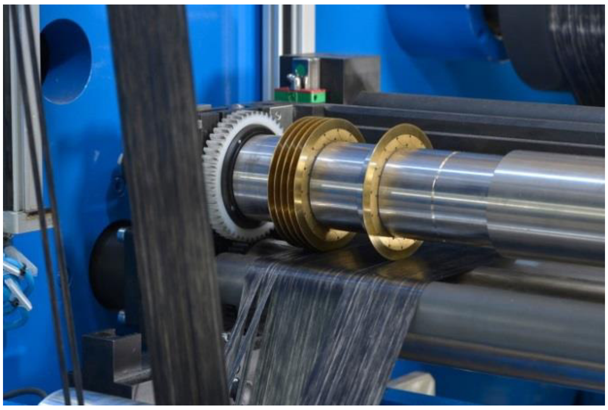
In the defined process window the weight-specific energy demand varies between -65% and over +7000%. As the baseline (0%) the medium production setup was chosen.

The main influencing parameters for lab scale presses are the type of heat generation, followed by the part thickness and process time.



* Combining all parameters, which are leading to a low and to a high process energy demand

4.12 Auxiliary processes

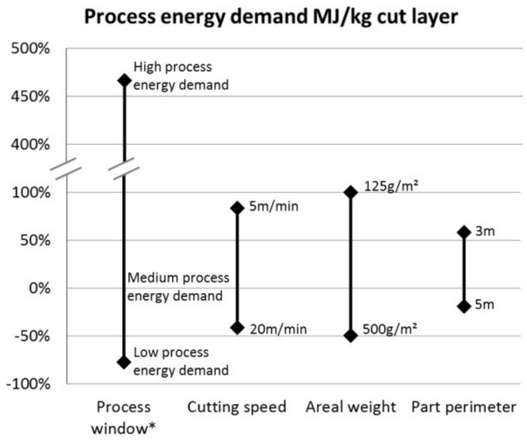


The processing of carbon fiber reinforced plastics requires different auxiliary processes in between:

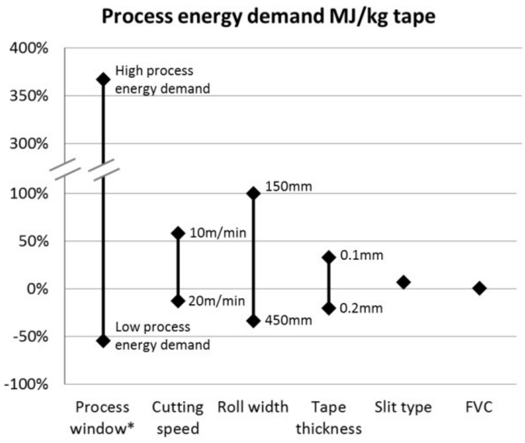
- CNC cutter for tailoring flat textiles
- Guillotine shears for cutting organosheets
- Slitting machine to provide the required tape/ tow width for tape laying and fiber placement
- 3D cutter for trimming the 3D preform
- Dissolver for resin mixing
- Injection devices for RTM and pultrusion
- Vacuum pump for RTM

The energy demands depending on the adjustable process parameters were measured for all mentioned processes. The results of the four highest energy consumers are presented in the following.

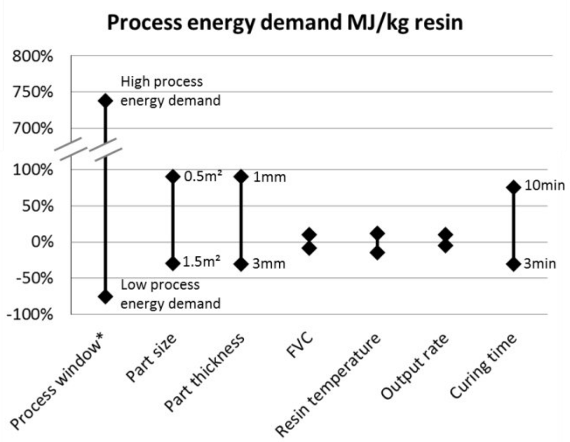
CNC cutter



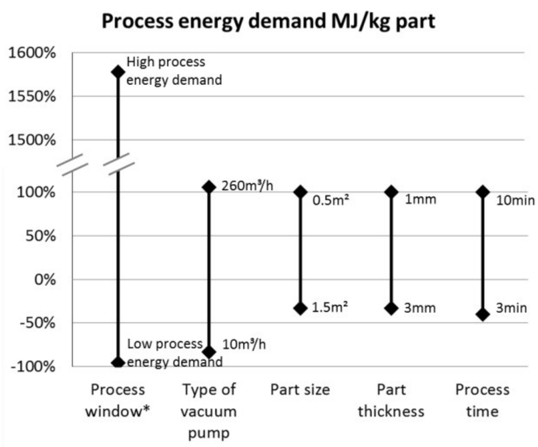
Slitting machine



High pressure injection device



Vacuum pump



* Combining all parameters, which are leading to a low and to a high process energy demand

5 Environmental impact of CFRP process chains

The life cycle analysis in this chapter is based on conventional and innovative production processes for the manufacturing of thermoset and thermoplastic based CFRP structures. The investigations focus on the identification of relevant production parameters. Therefor the process energy demand for different production scenarios is analyzed with the OFAT method. Based on the results the environment impact is determined. For the life cycle assessment three production scenarios are considered: One which combines all parameters leading to a low process energy demand, one which results in a medium process energy demand and another production scenario leading to the highest process energy demand in the evaluated process window.

While the process energy demand in the manufacturing phase fluctuates across the different production scenarios, the environmental burden of the material production is kept constant. The process parameters for the material production are shown in Table 7. For carbon fibers an average global production scenario is chosen. Life cycle inventory data for PAN-fiber production and matrix system are taken from the GaBi professional database. For modelling the environmental burden caused by the energy consumption in the manufacturing phase, the German electricity grid mix is considered [31]. All parameters leading to a 10% fluctuation of the weight-specific process energy demand at least are varied. A detailed overview of all boundary conditions for each process chain is given in the appendix C.2.

The SotA process chain includes preforming of textiles with an infrared heater and a forming press. The infiltration is realized with RTM technology. For fiber reinforced thermoplastic structures, the processing of fabric reinforced organosheets is considered. This implies the use of an infrared heater to heat the organosheet to its melting temperature and a press to apply the required forming pressures. For a defined crystallization a self-heated tool is usually used for forming.

Table 7: Boundary conditions for material manufacturing

Parameter	Specification	Remarks
PAN-fiber production		
Base country	Japan	Dataset in GaBi professional database [27], adapted from base country EU-28 to Japan
Type	Polyacrylonitrile (PAN) fiber	
Carbon fiber production		
Base country	Global	For the carbon fiber production, a global energy mix is calculated according to the global distribution of carbon fiber production capacities as given in [28] using the corresponding energy generation datasets in GaBi professional database [29].
Type	HT fiber	
Mass losses	~ 50% from PAN to carbon fiber	
Fiber density	1.78 g/cm³	
Matrix		
Base country	Europe	Available dataset in GaBi professional database [30]
Type	Epoxy resin | PA6	
Matrix density	1.17 g/cm³ | 1.14 g/cm³	

In order to consider material-efficient production process chains, dry fiber placement and tailored fiber placement was used as low cut-off preforming technology for curved thermoset based production process chains. For both layup technologies a subsequent forming step and the infiltration is considered. Braiding and pultrusion represent the process chains for fiber reinforced thermoset profiles. While a subsequent infiltration step is considered for braiding, two different pultrusion setups are evaluated: On the one hand the impregnation of fibers through a resin bath using an epoxy resin is evaluated. On the other hand, a direct impregnation of the fibers in the pultrusion die, using a high reactive PU resin system is investigated.

For fiber reinforced thermoplastic parts, a material efficient tape laying as well as an automated fiber placement process are analyzed. Subsequent two-dimensional consolidation has been taken into account as an intermediate step in addition to the forming.

Even though the focus of this study is the evaluation of process chains suitable for the production of continuous fiber reinforced plastic parts, the production of nonwoven textiles is also considered. The reason for this approach was the request to investigate at least one manufacturing route which allows the reintroduction of carbon fiber cut-offs into the value-added chain. Two different wet laid nonwovens were analyzed, one out of 100% recycled carbon fibers and one mixed with thermoplastic fibers. The subsequent process steps are comparable with the SotA thermoset and thermoplastic based process chains. An overview of the considered process chains in this chapter is given in Figure 4.

The different production process chains and scenarios are compared in three relevant categories:

- Global warming potential (GWP) relates to the emission of greenhouse gases to the atmosphere, contributing to anthropogenic climate change. The GWP is given in kg CO_2 equivalent.
- Primary energy demand (PED) relates to the use of non-renewable resources (nrr) as energy carriers. It is given in MJ of lower heating value (lhv).
- Abiotic depletion potential (ADP) also relates to non-renewable resources, but includes a characterization of the resources by scarcity. ADP is also given in MJ.

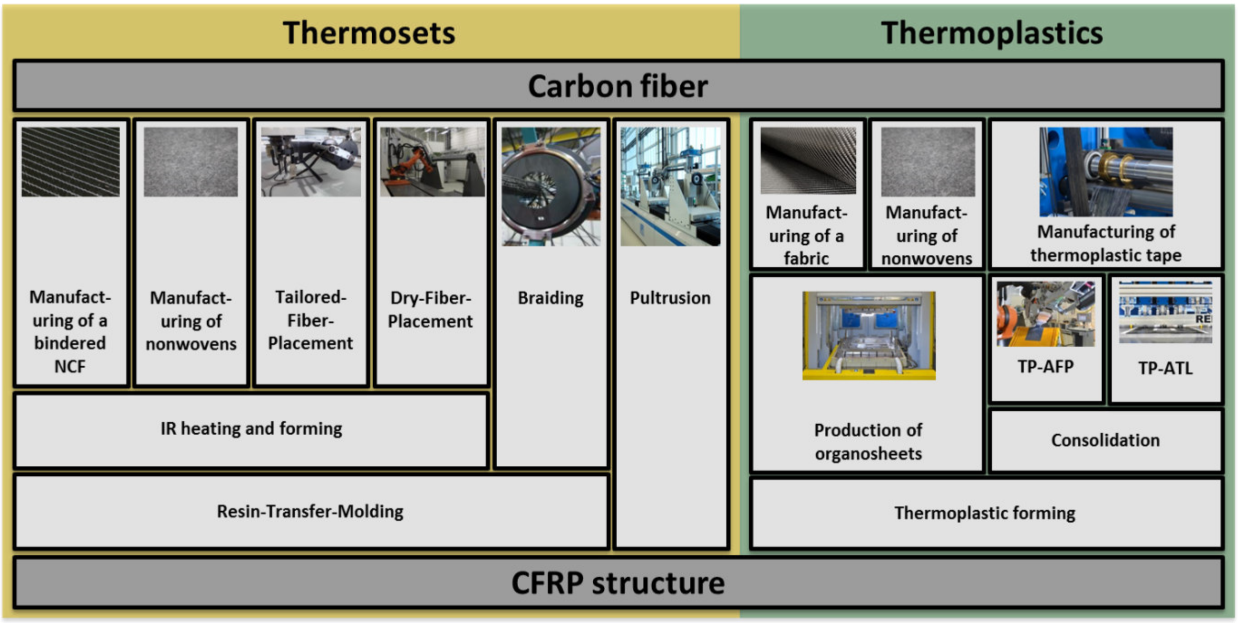


Figure 4: Overview of investigated process chains (read from top to bottom, i.e. from fiber to structure)

5.1 NCF-RTM process chain

In the automotive industry, flat bindered textiles are typically used for the production of cupped continuous reinforced CFRP parts. Several layers are tailored and stacked to a preform. To obtain a 3D preform, an additional forming step has to be applied. Hereby the 2D stack is heated up to the softening temperature of the binder using contact or infrared heating systems. Subsequent forming is conducted in a press. Afterwards the preform is trimmed. Apart from wet compression molding, the most commonly used technology for preform infiltration is RTM. A resin-hardener mixture is injected at pressures of up to 100 bar into a closed cavity containing the 3D preform. For a homogeneous compaction of the preform and to ensure a tight tooling, the RTM tool is clamped together by a press. Injection and curing then usually take place at isothermal temperatures, using self-heated tools with curing temperatures in the range of 80 °C to 130 °C.

Results of the OFAT energy analysis

Combining all parameters leading to a low process energy demand results in 72% reduction, whereas the worst-case scenario leads to a 680% increase compared to the medium production setup.

Main influencing parameters are:

- Part size and thickness
- Curing time

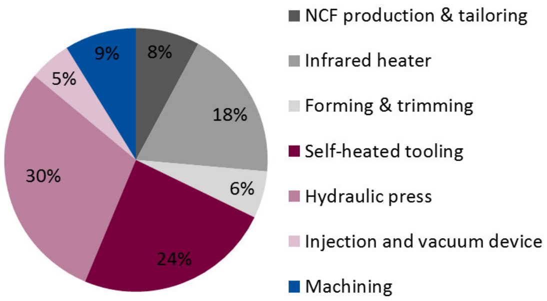
Optimization potential

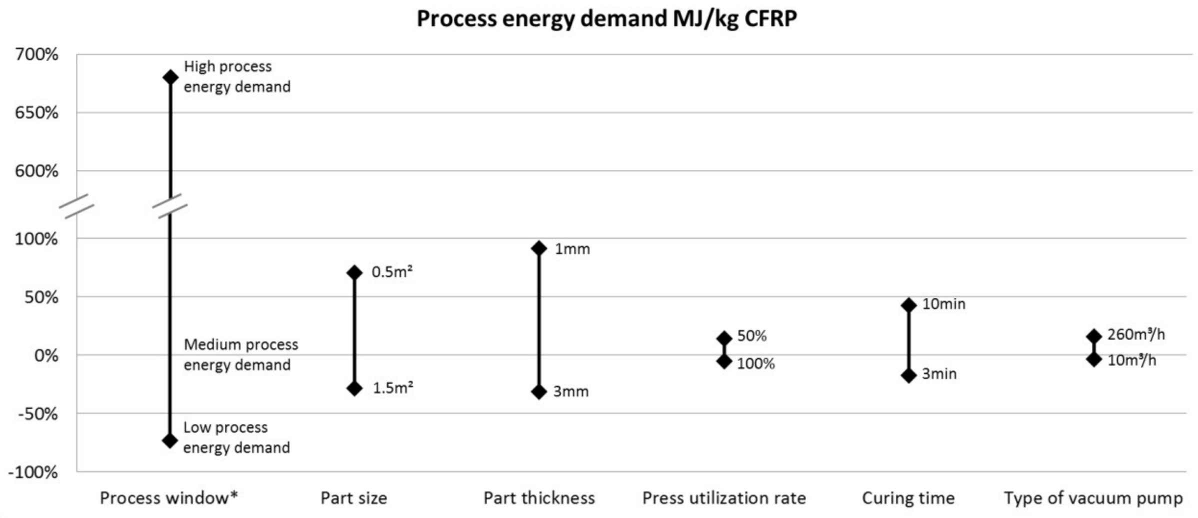
The part size and thickness are usually fixed in a production series. The next potential point for optimization is the reduction of the curing time by e. g. increasing the curing temperature. The impact of a temperature increase is below 10% and could be outweighed by the shortened curing time.

Share of process steps

Dominating consumers for a medium production setup are the hydraulic press, the self-heated tooling and the IR heater.

All varied parameters and made assumptions are listed in Table 37 in the appendix C.2.



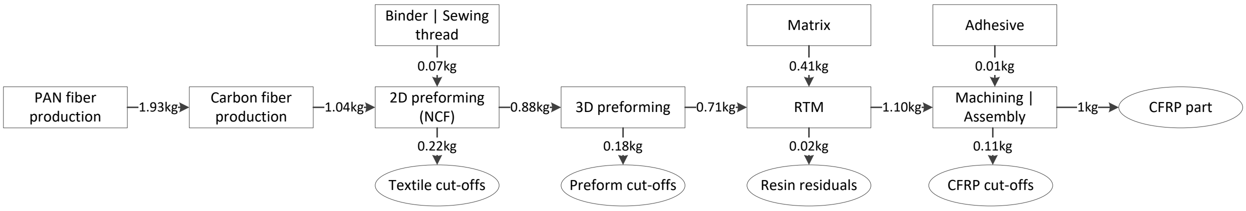


* Combining all parameters, which are leading to a low and to a high process energy demand

NCF-RTM process chain

Material flow

The use of flat textiles is linked to cut-offs in tailoring of textiles and trimming of 3D preforms for RTM tooling. Depending on part geometry and textile roll width, the number of cut-offs can vary significantly. For the evaluation, the average cut-off for each process step is estimated at 20%. For each process chain, finishing by milling is assumed, with a 10% cut-off rate. A detailed overview of all parameters relevant for the material flow and the process energy demand is given in Table 37 in the appendix C.2.



Life cycle impact assessment

The production setup itself and the corresponding process energy demand have an impact on the results across all indicators. Deviating from the medium setup leads to a

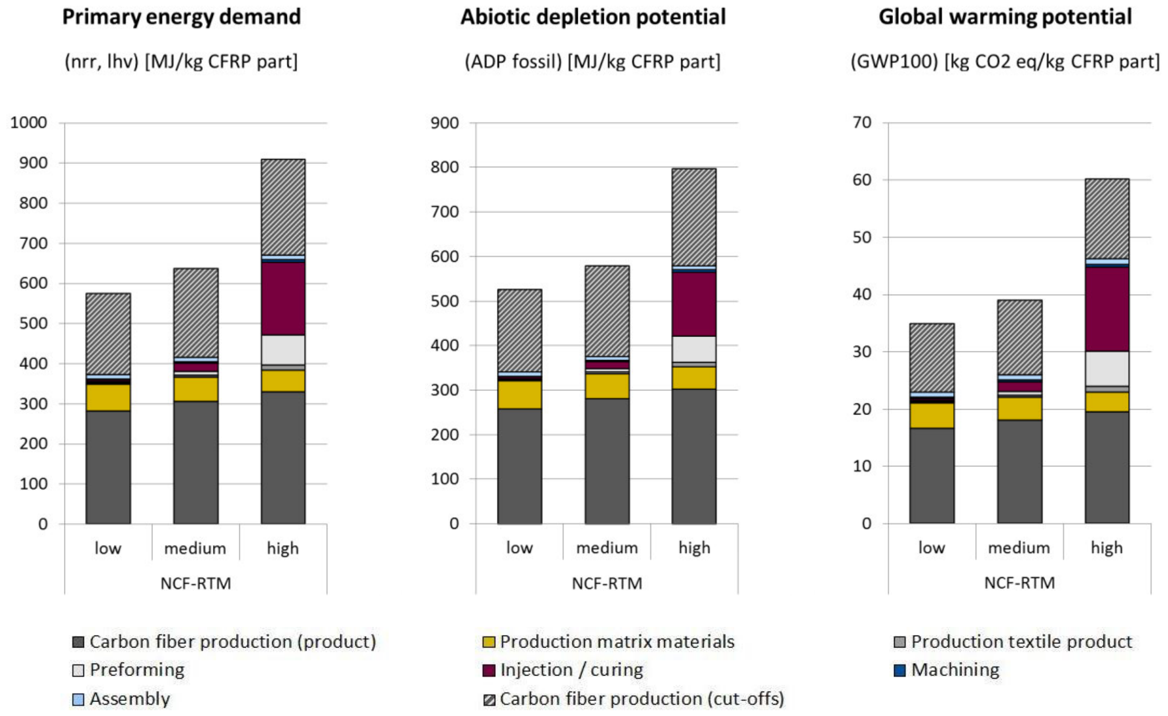
- PED between -10% and 43%
- ADP between -9% and 38%
- GWP between -11% and 55%

For a medium or low process energy setup, the carbon fiber production (w/o cut-offs) has a share of around 46 to 48% in each impact category, which decreases to 36 to 38% for a high process energy production setup.

The main drivers are the impacts of the preforming and injection/ curing steps, which increase by a factor of seven between the medium and high setup. Overall, this leads to a strongly increased share of the processing technologies of

- 32% compared to 8% of PED
- 29% compared to 7% of ADP
- 39% compared to 10% of GWP

of the medium production setup. The LCIA results in other investigated impact categories exhibit the same tendency.



5.2 Nonwovens-RTM process chain

Nonwovens, especially those from glass fibers, are typically used to realize good surface qualities. However, the recycling of carbon fibers (cut-offs and pyrolysis fibers) is becoming increasingly important. The production of nonwovens is one possibility to enable a further processing of recycled fibers with SotA technologies. For a thermoset-based process chain, nonwovens are typically stabilized with a binder during fabrication. The subsequent process steps are similar to the NCF-RTM process chain. The textiles are cut, stacked and then formed into the final 3D shape. Resin transfer or wet compression molding can be used for the infiltration.

However, compared to a continuous fiber textile, the process parameters might be adapted to ensure a defined preform compaction and to prevent race tracking and fiber washout. Besides that, in this study the FVC was set to 50% ensuring comparability with other process chains although a maximum FVC of 40% is achievable today. The production of high-value and cost-efficient products still requires a lot of research regarding textile performance and further processing. Furthermore, for the design of a structure the performance of these materials must be reliably predictable.

Results of the OFAT energy analysis
The weight-specific process energy demand is fluctuating between -63% and +490% compared to the medium production setup.

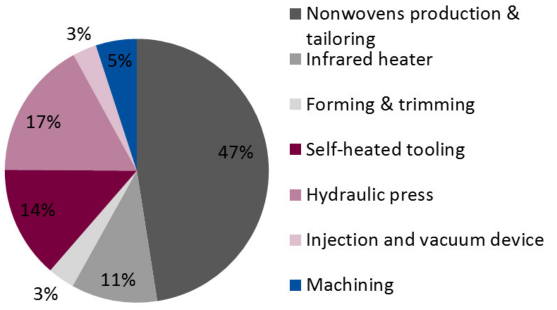
Main influencing parameters are:

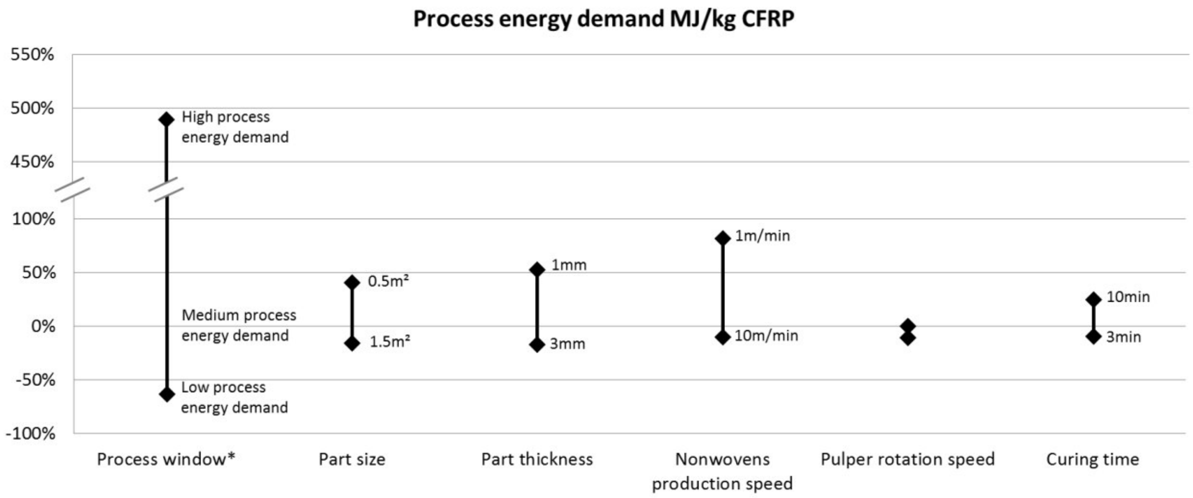
- Production speed nonwovens
- Part size and thickness

Optimization potential
Data were gained only in lab-scale. The width of nonwovens was fixed to 0.31 m and the maximum production speed limited to 10 m/min. Typically wet-laid technologies, e. g. for paper manufacturing have a considerably higher throughput. An adaption of these technologies for carbon fibers is therefore one measure for optimization.

Share of process steps
Dominating consumer for a medium production setup is the production of nonwovens. As process data acquisition could only be done in lab scale, reliable statements for a serial production cannot be made.

All varied parameters and made assumptions are listed in Table 38 in the appendix C.2.





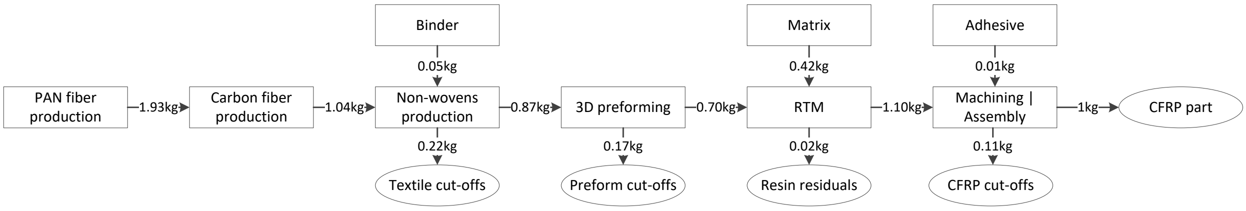
* Combining all parameters, which are leading to a low and to a high process energy demand

Nonwovens-RTM process chain

Material flow

Wet-laid nonwovens require, apart from fibers and binder, water and dispersing agents for the production. However, only the structural material flow is presented in the following. For the evaluation, the average cut-off for each process step is estimated at 20%.

For each process chain, finishing by milling is assumed, with a 10% cut-off rate. A detailed overview of all parameters relevant for the material flow and the process energy demand is given in Table 38 in the appendix C.2.



Life cycle impact assessment

The production setup itself (except assembly) and the corresponding process energy demand have an impact on the results across all indicators. Deviating from the medium setup leads to a

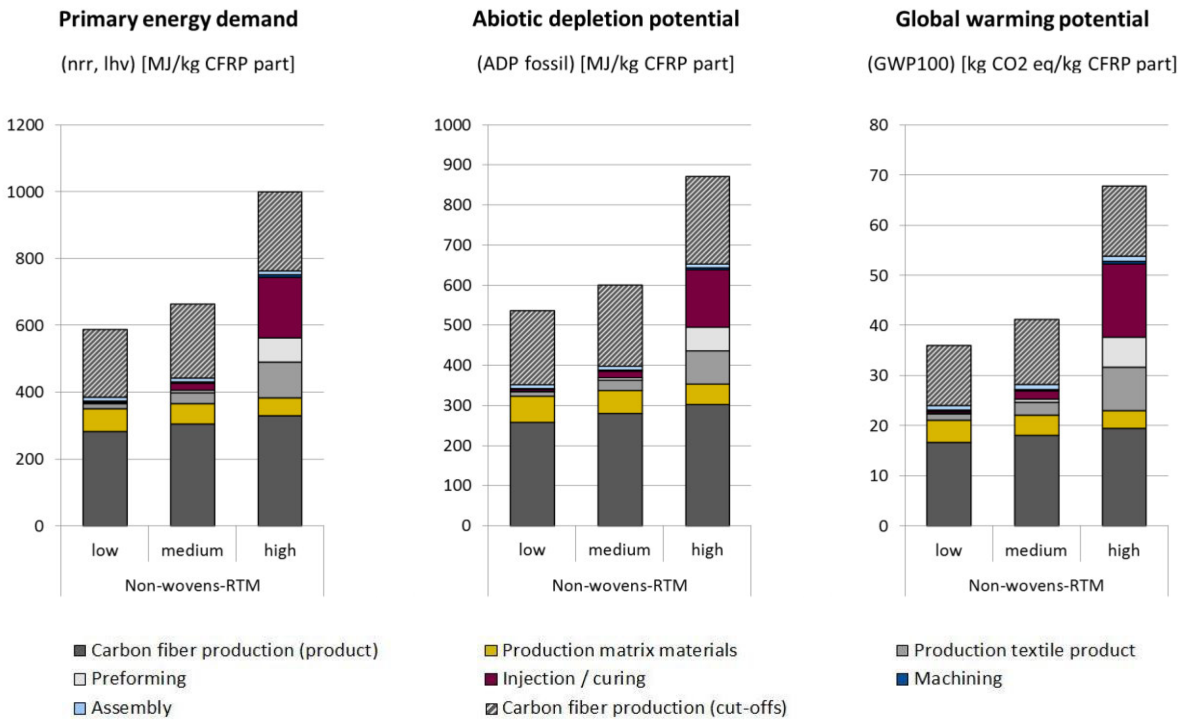
- PED between -11% and 51%
- ADP between -11% and 45%
- GWP between -13% and 65%

For a medium process energy setup, the carbon fiber production (w/o cut-offs) has a share of around 44 to 47% in each impact category, which decreases to 29 to 35% for a high process energy production setup.

The main drivers are the impacts of the preforming and injection/ curing steps, which increase by a factor of seven between the medium and high setup. Overall, this leads to a strongly increased share of the processing technologies of

- 38% compared to 11% of PED
- 34% compared to 10% of ADP
- 45% compared to 15% of GWP

of the medium production setup. The LCIA results in other investigates impact categories exhibit the same tendency.



5.3 TFP-RTM process chain

Tailored Fiber Placement enables load-path adapted fiber orientation as well as near net shape layup. This well-automated preforming technology is already used for the production of helicopter and automotive components as well as for products in the machinery, sports and leisure sectors. The subsequent processing steps are quite similar to a standard textile process chain. The final stitched stack is formed and infiltrated. Depending on the application, different liquid composite molding technologies can be applied.

In this study the RTM technology with the following process parameters is considered. The resin-hardener mixture is injected at pressures of up to 100 bar into a closed cavity containing the 3D preform. For a homogeneous compaction of the preform and to ensure a tight tooling, the RTM tool is clamped together by a press. Injection and curing then usually take place at isothermal temperatures, hereby self-heated tools with curing temperatures ranging between 80 °C and 140 °C are used.

Results of the OFAT energy analysis

Combining all parameters leading to a low process energy demand results in 72% reduction, whereas the worst-case scenario leads to a 730% increase compared to the medium production setup.

Main influencing parameters are:
- Part size and thickness
- Curing time

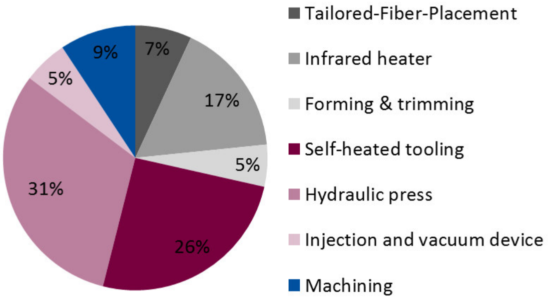
Optimization potential

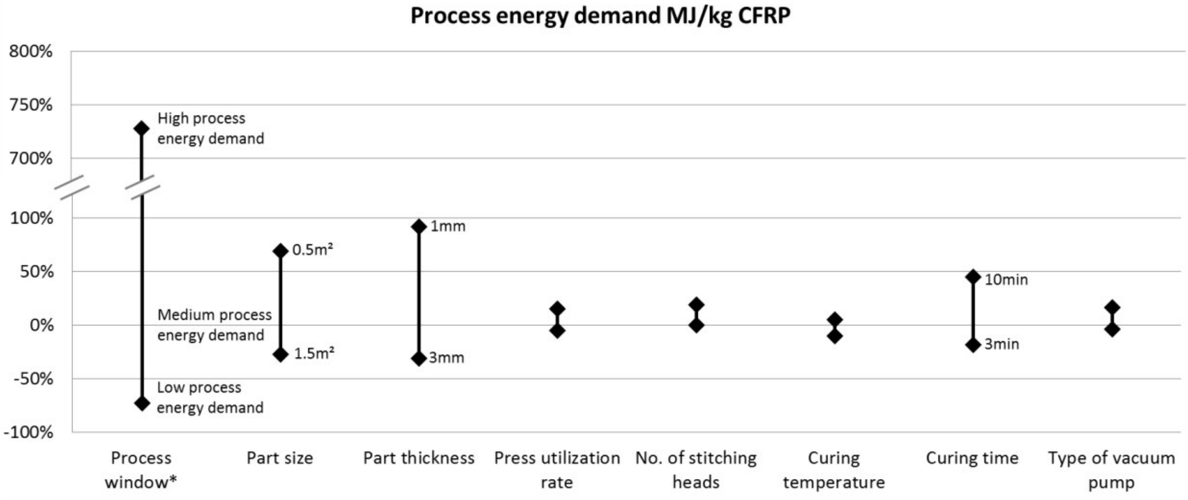
As the part size and thickness are usually fixed in a production series, the optimization potential is limited. One potential point for optimization is the reduction of the curing time by e.g. increasing the curing temperature as the impact of a temperature increase (up to 140 °C) is far below 10%.

Share of process steps

Dominating consumers for a medium production setup are the hydraulic press, the self-heated tooling and the IR heater.

All varied parameters and made assumptions are listed in Table 39 in the appendix C.2.

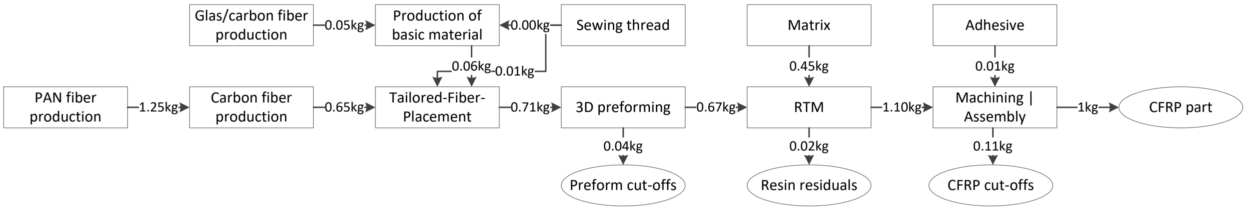




* Combining all parameters, which are leading to a low and to a high process energy demand

Material flow

As basic material a 125 g/m² glass/carbon fiber non-crimp-fabric is considered for the balance. The amount of stitching yarn is fixed to 1.6% of the carbon fiber input. Possible fiber residuals on the spools are neglected. TFP enables a near net shape preforming, therefore only 5% cut-offs are estimated for the preform trimming. A detailed overview of all parameters relevant for the material flow and the process energy demand is given in Table 39 in the appendix C.2.



Life cycle impact assessment

The production setup itself (except assembly) and the corresponding process energy demand have an impact on the results across all indicators. Deviating from the medium setup leads to a

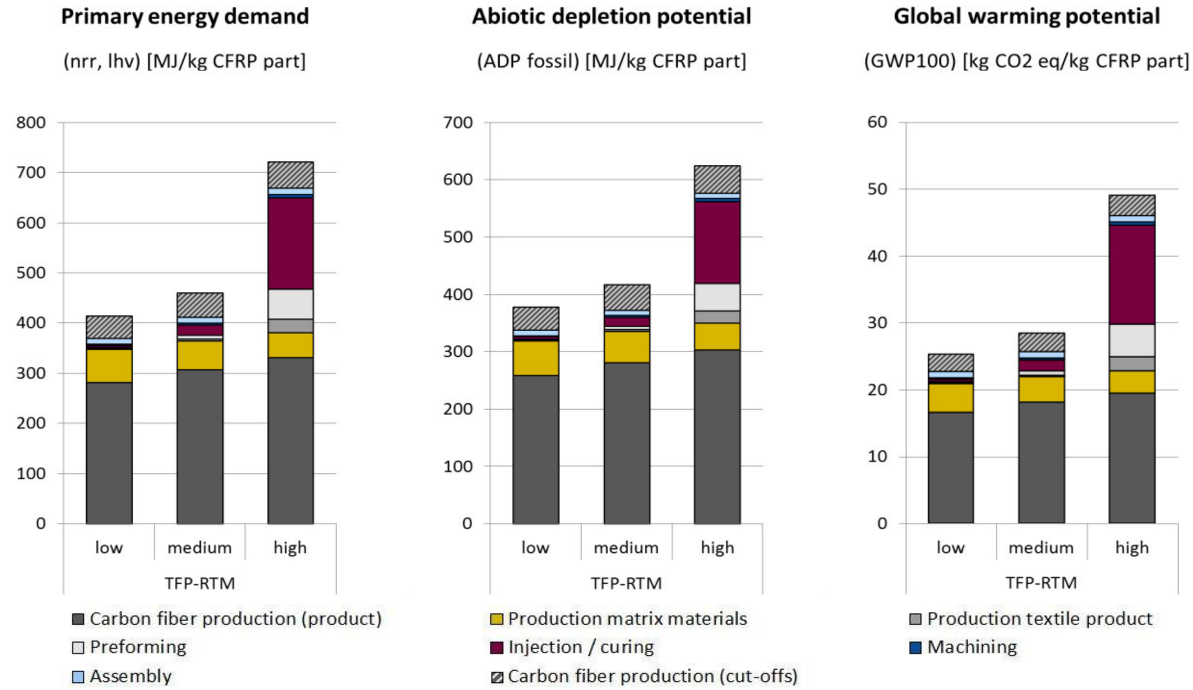
- PED between -10% and 57%
- ADP between -9% and 50%
- GWP between -11% and 73%

For a medium process energy setup, the carbon fiber production (w/o cut-offs) has a share of around 64 to 68% in each impact category, which decreases to 40 to 48% for a high process energy production setup.

The main drivers are the impacts of the preforming and injection/ curing steps, which increase by a factor of seven between the medium and high setups. Overall, this leads to a strongly increased share of the processing technologies of

- 40% compared to 10% of PED
- 36% compared to 9% of ADP
- 47% compared to 13% of GWP

of the medium production setup. The LCIA results in other investigated impact categories exhibit the same tendency.


Primary energy demand

(nrr, lhv) [MJ/kg CFRP part]

Abiotic depletion potential

(ADP fossil) [MJ/kg CFRP part]

Global warming potential

(GWP100) [kg CO2 eq/kg CFRP part]

5.4 DFP-RTM process chain

For the evaluation of the DFP-RTM process chain, the use of a roving with a separate binder application is assumed. Therefore, the manufacturing of a semi-finished product, e.g. binder yarn is not considered. Besides that, in this study a robot based layup technology is analyzed. Still the preform is placed in 2D and then formed into its 3D shape. Reasons are, among others, that a direct 3D layup would result in longer process times and for most parts due to their complexity a final forming step is required. For draping the 2D stack into its 3D shape an infrared heating system for binder activation and a press are considered. The subsequent process steps are similar to the other preforming technologies. The preform is trimmed and infiltrated with resin applying the RTM technology.

The automated material efficient layup is one of the advantages of this technology. However, the infiltration of the compact preform is still challenging. Also, the robust feeding and cutting of low cost material offers further optimization potentials.

Results of the OFAT energy analysis

In best case a 77% reduction and in worst case a 610% increase of the process energy demand compared to the medium production setup was calculated

Main influencing parameters are:

- Part size and thickness
- Curing time

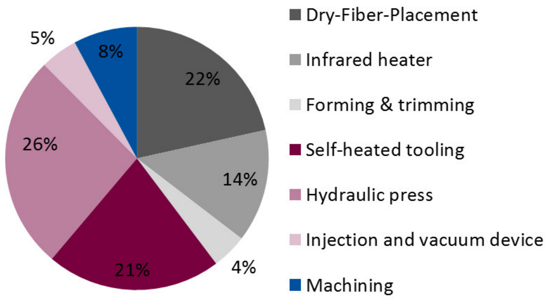
Optimization potential

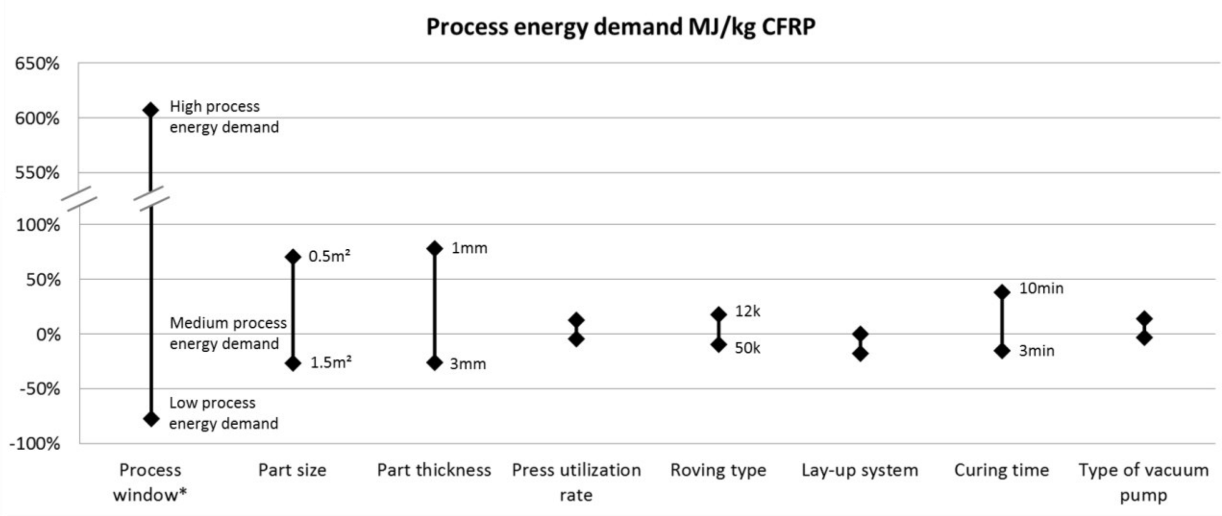
As part size and thickness are usually fixed in a production series, the optimization potential is limited. One potential point for optimization is the reduction of curing time. Besides that, the energy consumption for layup is dominated by compressed air. An alternative cooling system for the placement head could increase the energy efficiency.

Share of process steps

Dominating consumers for a medium production setup are the hydraulic press, the layup technology and the self-heated tooling.

All varied parameters and made assumptions are listed in Table 40 in the appendix C.2.

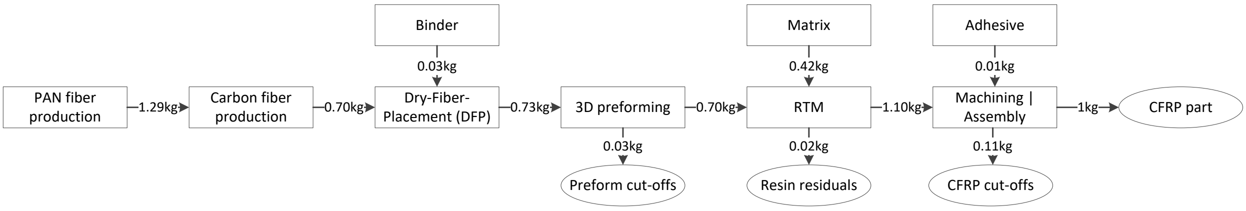




* Combining all parameters, which are leading to a low and to a high process energy demand

Material flow

Due to the near net shape layup only minor cut-offs occur. In this study 5% of the material input for trimming the preform to the required RTM tool shape is considered. Any fiber residues on the spools are neglected. Similar to NCF, 5% of binder is assumed for the fixation of the stack and preform. Again, for machining a 10% cut-off rate is estimated. A detailed overview of all parameters relevant for the material flow and the process energy demand is given in Table 40 in appendix C.2.



Life cycle impact assessment

The production setup itself (except assembly) and the corresponding process energy demand have an impact on the results across all indicators. Deviating from the medium setup leads to a

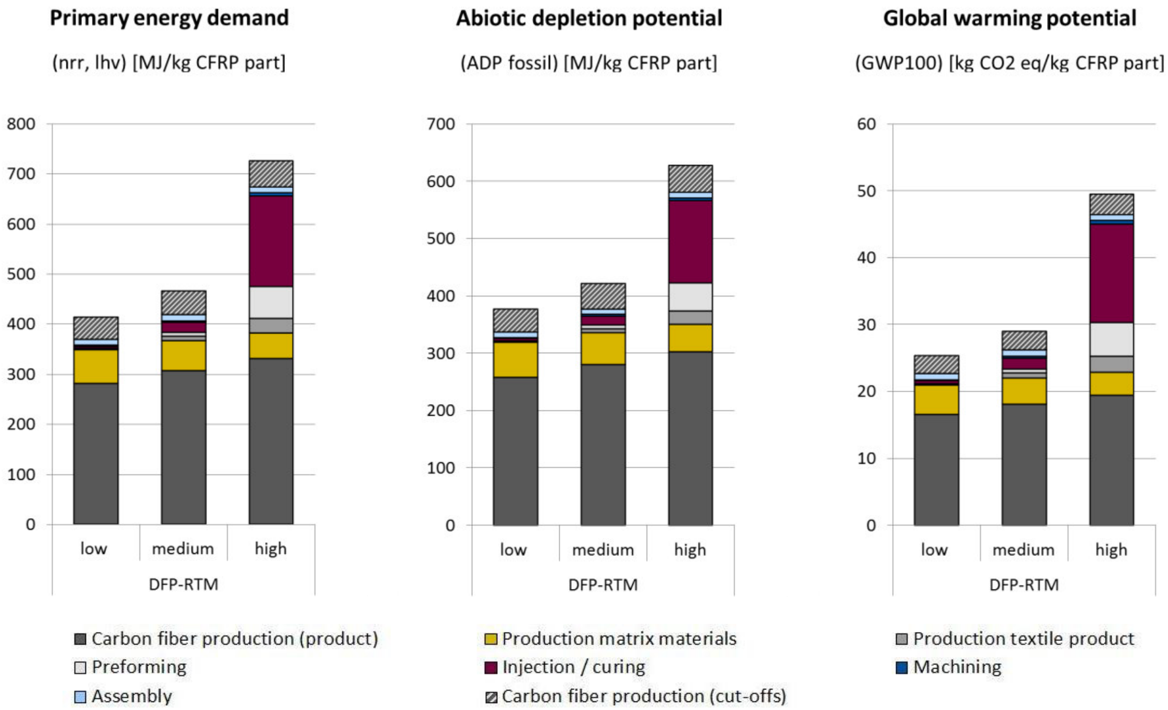
- PED between -11% and 56%
- ADP between -10% and 49%
- GWP between -13% and 71%

For a medium process energy setup, the carbon fiber production (w/o cut-offs) has a share of around 62 to 67% in each impact category, which decreases to 39 to 45% for a high process energy production setup.

The main drivers are the impacts of the preforming and injection/ curing steps, which increase by a factor of seven between the medium and high setup. Overall, this leads to a strongly increased share of the processing technologies of

- 40% compared to 11% of PED
- 37% compared to 10% of ADP
- 48% compared to 14% of GWP

of the medium production setup. The LCIA results in other investigated impact categories exhibit the same tendency.



5.5 Braiding-RTM process chain

Braiding in combination with different liquid composite moldings is a well-established manufacturing chain for the production of curved profiles. Applications can be found in the automotive industry as well as in the sports and leisure sector. Depending on the part geometry, the preform can be braided directly in the final shape. Thus, the need of a binder as well as a further stabilization and forming step is often not required. Braiding cores remain either in the preform and part, are washed out after the infiltration, or are demolded and reused again. Afterwards the preform is trimmed.

RTM is, apart from wet compression molding, the most commonly used technology for preform infiltration. A resin-hardener mixture is injected at pressures of up to 100 bar into a closed cavity containing the 3D preform. For a homogeneous compaction of the preform and to ensure a tight tooling, the RTM tool is clamped together by a press. Injection and curing then usually take place at isothermal temperatures, hereby self-heated tools with curing temperatures ranging between 80°C and 140°C are used.

Results of the OFAT energy analysis

Combining all parameters leading to a low process energy demand results in 75% reduction, whereas the worst case scenario leads to a 760% increase compared to the medium production setup.

Main influencing parameters are:

- Part size and thickness
- Curing time

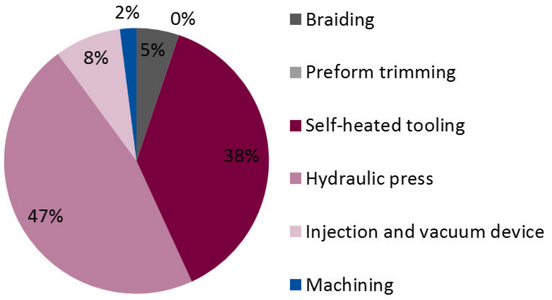
Optimization potential

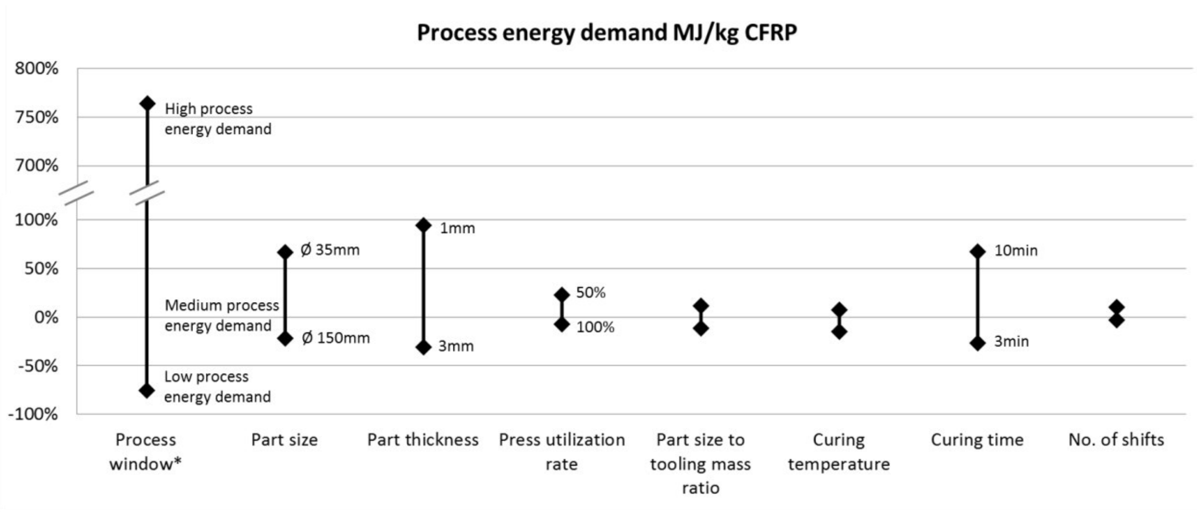
As the part size and thickness are usually fixed in a production series, the optimization potential is limited. One potential point for optimization is the reduction of the curing time by e.g. increasing the curing temperature as the impact of a temperature increase is far below 10%.

Share of process steps

Dominating consumers for a medium production setup are the hydraulic press and the self-heated tooling.

All varied parameters and made assumptions are listed in Table 41 in appendix C.2

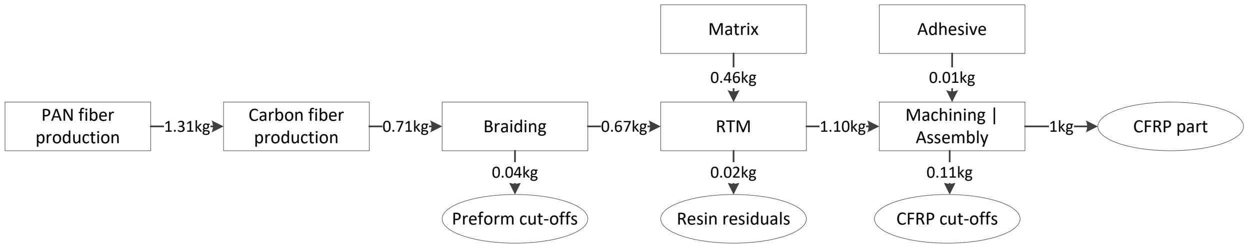




* Combining all parameters, which are leading to a low and to a high process energy demand

Material flow

In this study the preform is directly braided without any subsequent forming steps. Furthermore, a reusable braiding core is assumed and therefore not considered in the material flow and balance. For an exact fitting of the preform to the RTM tool cut-offs of 5% are estimated. Fiber residues on the spools are neglected. Further cut-offs of 10% for the final machining are considered. A detailed overview of all parameters relevant for the material flow and the process energy demand is given in appendix C.2.



Life cycle impact assessment

The production setup itself (except assembly) and the corresponding process energy demand have an impact on the results across all indicators. Deviating from the medium setup leads to a

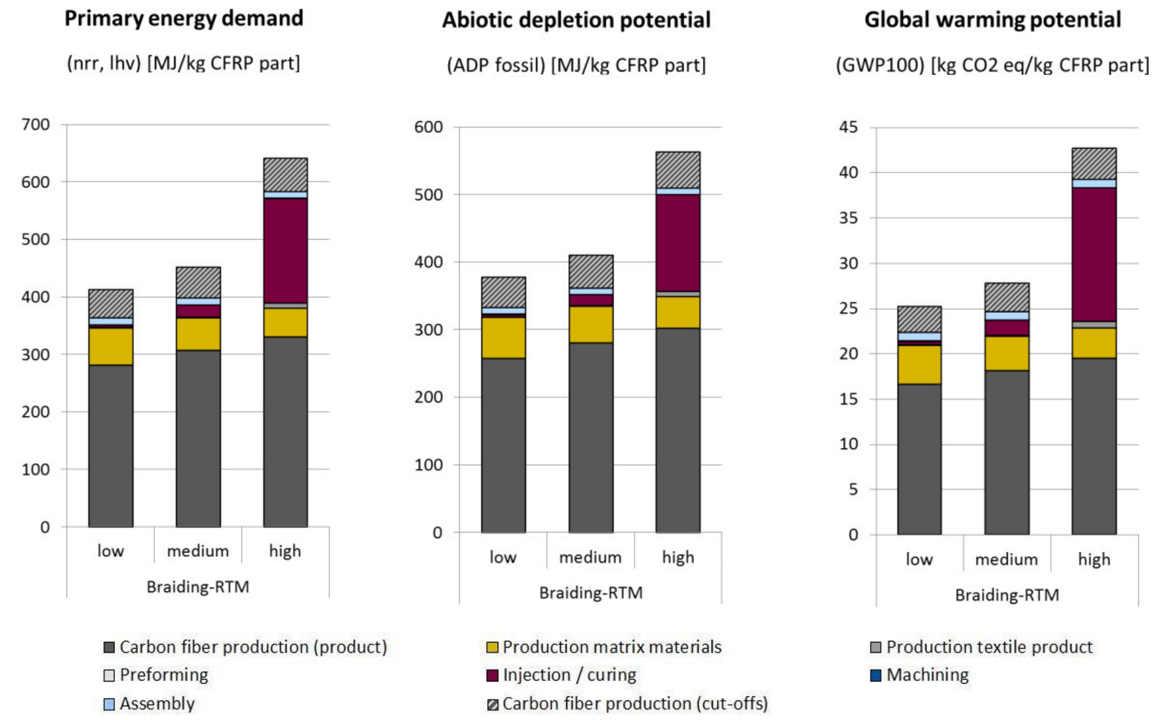
- PED between -8% and 42%
- ADP between -8% and 37%
- GWP between -9% and 54%

For a medium process energy setup, the carbon fiber production (w/o cut-offs) has a share of around 65 to 8% in each impact category, which decreases to 46 to 54% for a high process energy production setup.

The main drivers are the impacts of the injection/ curing steps, which increase by a factor of seven between the medium and high setup. Overall, this leads to a strongly increased share of the processing technologies of

- 32% compared to 7% of PED
- 28% compared to 7% of ADP
- 39% compared to 10% of GWP

of the medium production setup. The LCIA results in other investigated impact categories exhibit the same tendency.



5.6 Pultrusion

Pultrusion is a highly automated process for manufacturing fiber-reinforced composite profiles with different constant cross-sectional shapes. Mainly continuous fibers as uni-directional reinforcements are used, but also textiles can be pultruded. In particular dry fibers/ textiles are continuously pulled through guiding plates into a resin bath or an injection chamber. Subsequently the impregnated fibers are cured in an electrically heated tool. The pulling speed depends on the reactivity of the resin and the size of the heating zones, which is limited by the pulling force, among other factors. After passing through the tool the resin is typically, fully cross-linked and the profile is cut to the required length.

Pultruded profiles especially from glass fibers can be found in various industry sectors. However, research is still ongoing to increase the throughput and to extend the application areas, e. g. direct pultrusion of curved profiles, bi-stage resin or thermoplastic pultrusion enabling a subsequent forming or a change in the cross-section. Also, the combination with other preforming technologies, like braiding or winding, is investigated.

Results of the OFAT energy analysis
The weight-specific process energy demand is fluctuating between a 56% reduction and a 1890% increase compared to the medium production setup.

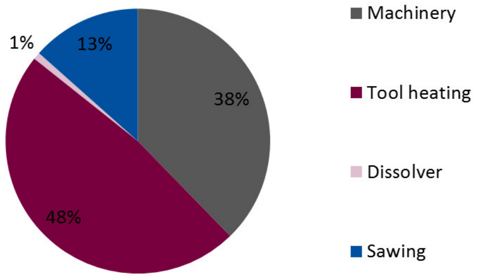
Main influencing parameters are:

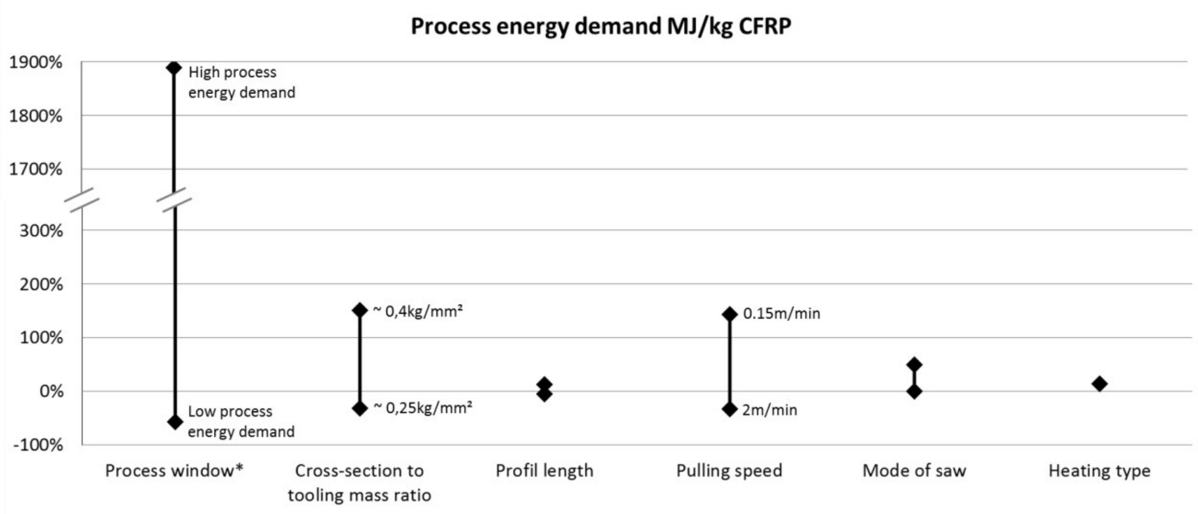
- Ratio cross-section to tooling mass
- Pulling speed

Optimization potential
A good tooling design as well as tooling adapted heating elements leading to low process energy demand. Besides that, increasing the pulling speed has a huge impact. This can be reached for example through the application of a closed mold impregnation in combination with a high reactive resin system or if possible an increase of tooling temperature.

Share of process steps
Dominating consumers for a medium production setup are the electric heated tooling and the machinery, here in detail the pulling of the pultruded part.

All varied parameters and made assumptions are listed in Table 42 in appendix C.2.



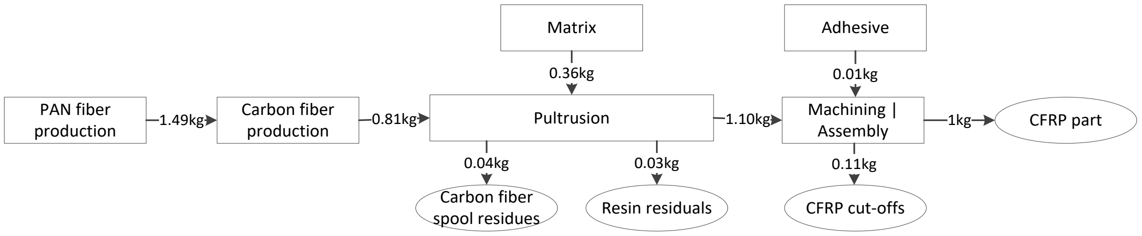


* Combining all parameters, which are leading to a low and to a high process energy demand

Pultrusion

Material flow

Pultrusion is a continuous processing of textiles and matrix. Material residues can therefore only occur at the beginning and the end of the process chain. In this study 5% fiber residuals on the spools are considered. The required amount of resin depends on the process design. For an open bath pultrusion 7.5% resin residuals are estimated. The low production setup evaluating a closed mold impregnation considers 5% leftovers in the injection device. A detailed overview of all parameters is given in appendix C.2.



Life cycle impact assessment

In this setup, there is no production of textile product, no preforming and no finishing, setting their respective shares to zero. Deviating from the medium setup leads to a

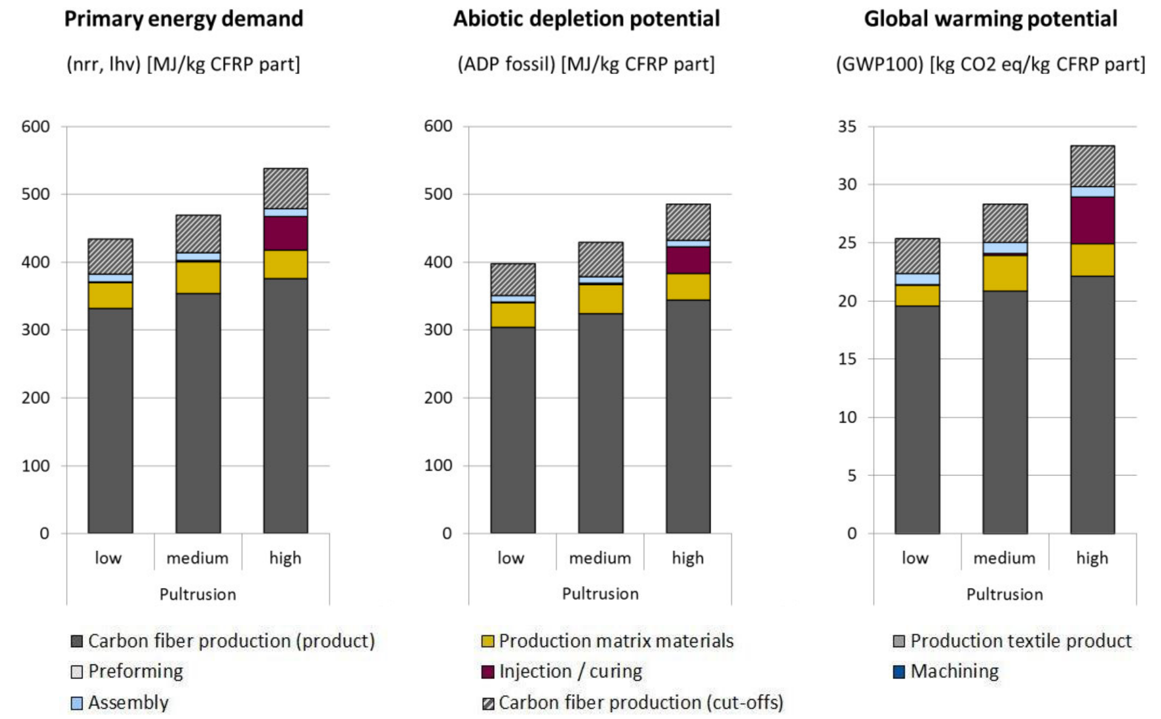
- PED between -8% and 15%
- ADP between -7% and 13%
- GWP between -10% and 18%

For medium process energy setup, the carbon fiber production (w/o spool residues) has a share of around 74 to 75% in each impact category, which decreases to 66 to 71% in best case.

The main driver is the impact of the pultrusion step, which increases by a factor of 22 between the medium and high setup. Overall, this leads to a strongly increased share of the processing technologies of

- 11% compared to 3% of PED
- 10% compared to 3% of ADP
- 15% compared to 4% of GWP

of the medium production setup. The LCIA results in other investigated impact categories exhibit the same tendency.



5.7 Fabric-organosheet-TP-forming process chain

Organosheets are typically made using injection molding and short fibers as reinforcements. However, organosheets with continuous fiber reinforcements are also available. The textile, usually a fabric, is impregnated with an extruded thermoplastic matrix. The required temperatures and pressures can be applied by a double-belt press or a continuous compression molding machine. Size and ply orientation are usually fixed. For further processing the sheet is trimmed to the required shape. The organosheet is heated up to the melting temperature of the matrix in an infrared heating system or contact heater and then formed into the final 3D geometry. For a defined crystallization the forming tool in the press is heated. In a small-scale production also variotherm forming in an oven or press is possible.

In this study a film impregnation of a carbon fiber fabric in a continuous compression molding machine was evaluated. For forming an IR heater, a press and a self-heated tooling was considered.

Results of the OFAT energy analysis

Combining all parameters leading to a low process energy demand results in 74% reduction, whereas the worst-case scenario leads to a 3360% increase compared to the medium production setup.

Main influencing parameters are:

- Press type
- Part size and thickness

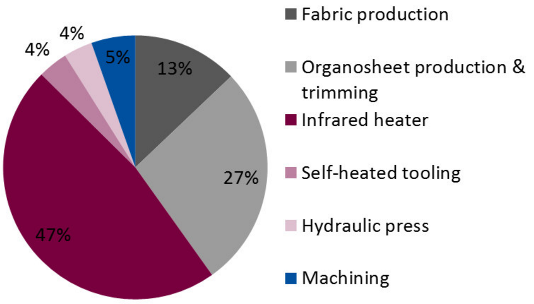
Optimization potential

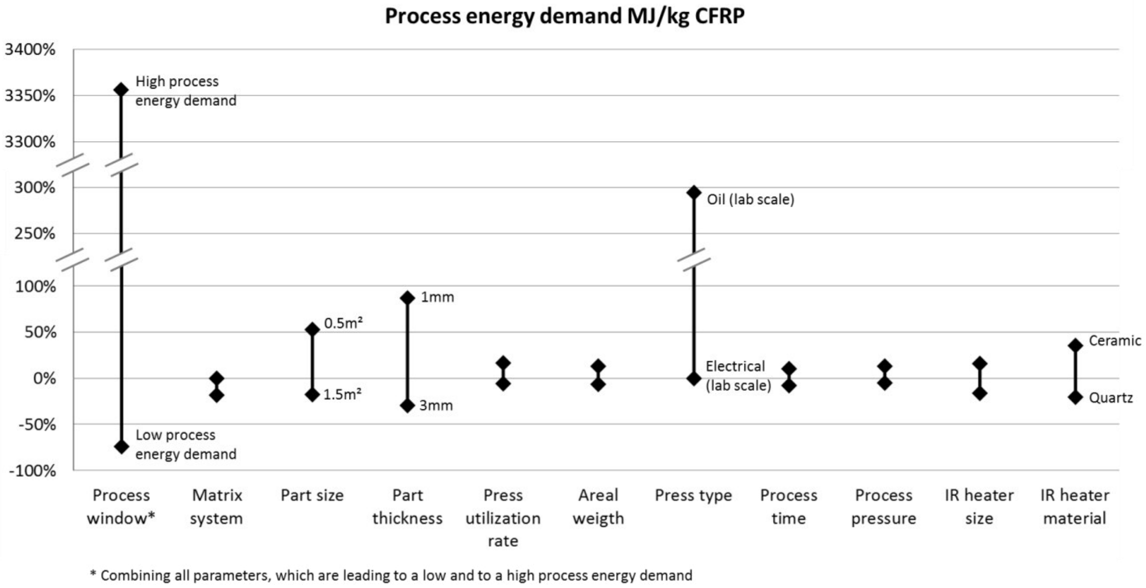
The data for the heating presses are gained only in lab scale; no reliable statements can be made. Furthermore, the part size and thickness are usually fixed in a production series. However, one potential point for optimization is the adaption of the IR heater to the part size.

Share of process steps

Dominating consumers for a medium production setup are organosheet production and IR heater. The latter is mainly caused by the areal utilization rate, whereas a 6 m² heating area for a 1 m² part is assumed.

All varied parameters are listed in appendix C.2.

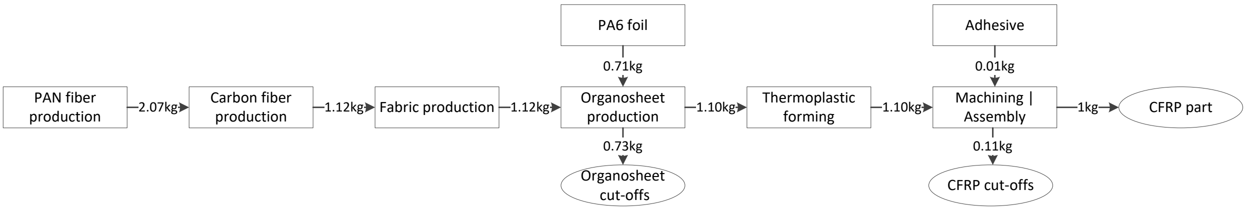




Fabric-organosheet-TP-forming process chain

Material flow

Before forming an organosheet to its final 3D geometry the size is already adapted to the required shape. Depending on part geometry and sheet size, the number of cut-offs can vary significantly. For the evaluation, an average cut-off of 40% is assumed. Possible cut-offs in fabric and organosheet production are neglected. 10% cuttings during machining are considered. A detailed overview of all parameters relevant for the material flow and the process energy demand is given in Table 43 in appendix C.2.



Life cycle impact assessment

The production setup itself (except assembly) and the corresponding process energy demand have an impact on the results across all indicators. Deviating from the medium setup leads to a

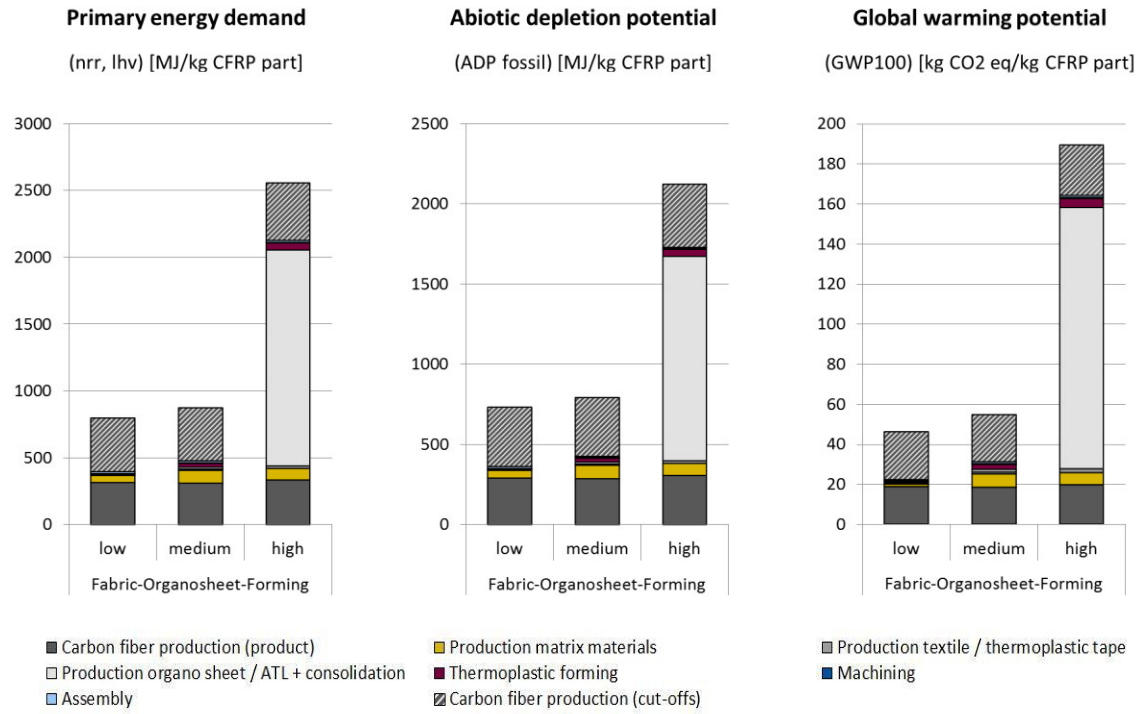
- PED between -9% and 192%
- ADP between -8% and 168%
- GWP between -15% and 248%

For a medium process energy setup, the carbon fiber production (w/o cut-offs) has a share of around 33 to 36% in each impact category, which decreases to 10 to 14% for a high process energy production setup.

The main driver is the impact of the organosheet production and consolidation, which increases by a factor of 100 between the medium and high setup. Overall, this leads to a strongly increased share of the processing technologies of

- 67% compared to 8% of PED
- 63% compared to 7% of ADP
- 73% compared to 11% of GWP

of the medium production setup. The LCIA results in other investigated impact categories exhibit the same tendency.



5.8 TP-nonwovens-organosheet-TP-forming process chain

Nonwovens, especially those from glass fibers, are typically used to realize good surface qualities. However, the recycling of carbon fibers (cut-offs and pyrolysis fibers) is becoming increasingly important. The production of nonwovens is one possibility to enable a further processing of recycled fibers with SotA technologies. For a thermoplastic-based process chain, nonwovens are typically mixed with thermoplastic fibers during fabrication. The subsequent process steps are similar to the organosheet production. The nonwovens are cut, stacked and consolidated in a double-belt press or continuous compression molding machine. Size and ply orientation are usually fixed. For further processing the sheet is trimmed to the required shape and heated up to the melting temperature. The forming takes place in a self-heated tooling, ensuring a defined crystallization, and a press. In a small-scale production also variotherm forming in an oven or press is possible. The production of high-value and cost-efficient products still requires a lot of research regarding textile performance and further processing. Furthermore, for the design of a structure the performance of these materials must be reliably predictable.

Results of the OFAT energy analysis

The weight-specific process energy demand fluctuates between -63% and +2045% compared to the medium production setup.

Main influencing parameters are:

- Press type
- Production speed nonwovens

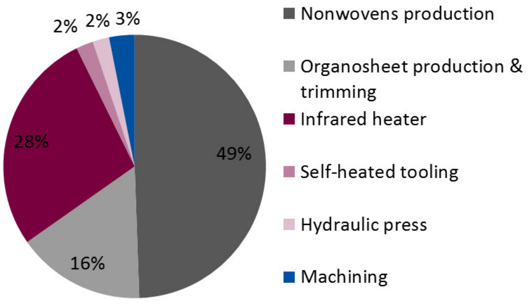
Optimization potential

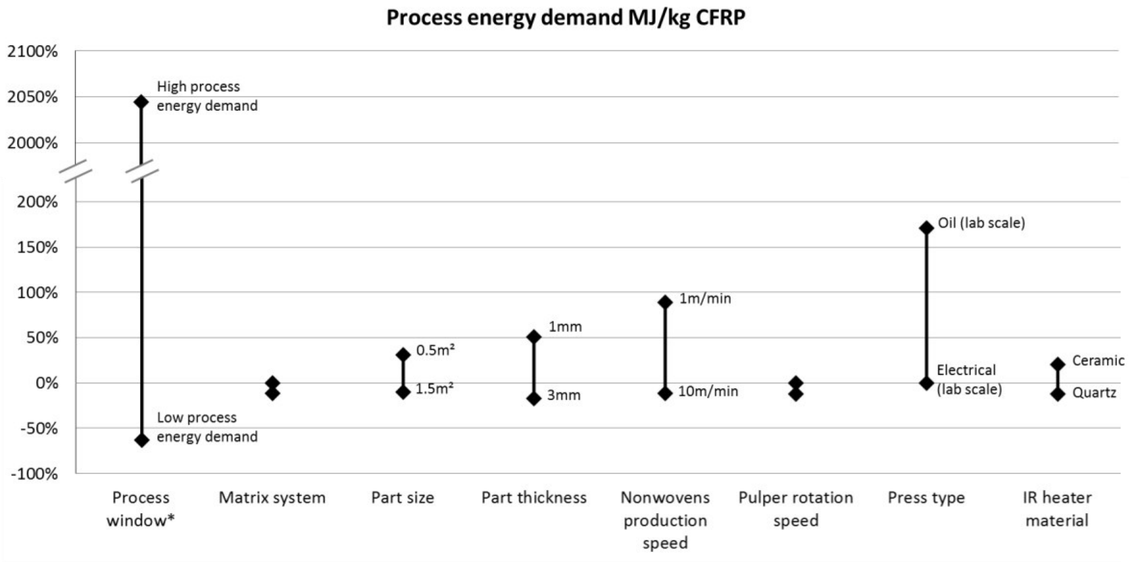
As the data for heating presses and nonwovens are gained only in lab scale, no reliable statements can be made. Typically, wet-laid technologies (e. g. for paper manufacturing) have a considerable higher throughput than measured. The adaption of these technologies for carbon fibers is therefore one measure for optimization.

Share of process steps

Dominating consumers for a medium production setup are nonwovens production and IR heater. As data acquisition could only be done in lab scale, reliable statements for serial production cannot be made.

All varied parameters are listed in appendix C.2.





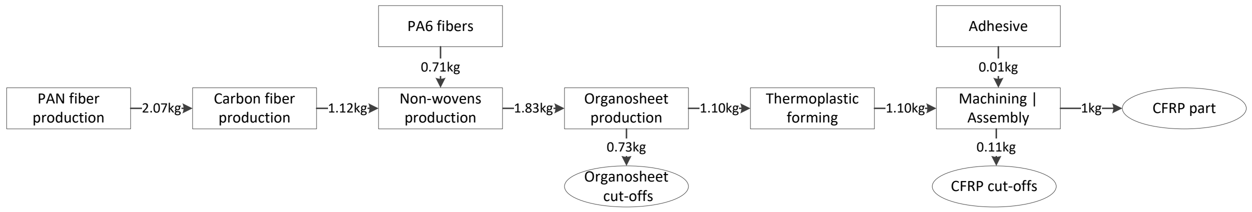
* Combining all parameters, which are leading to a low and to a high process energy demand

TP-nonwovens-organosheet-TP-forming process chain

Material flow

To enable a comparison with other process chains a FVC of 50% is considered. However, available nonwovens organosheets have a FVC far below 40%. The main cut-offs are again occurring before the forming. In this study 40% are assumed.

For each process chain, finishing by milling is assumed, with a 10% cut-off rate. A detailed overview of all parameters relevant for the material flow and the process energy demand is given in Table 44 in the appendix C.2.



Life cycle impact assessment

The production setup itself (except assembly) and the corresponding process energy demand have an impact on the results across all indicators. Deviating from the medium setup leads to a

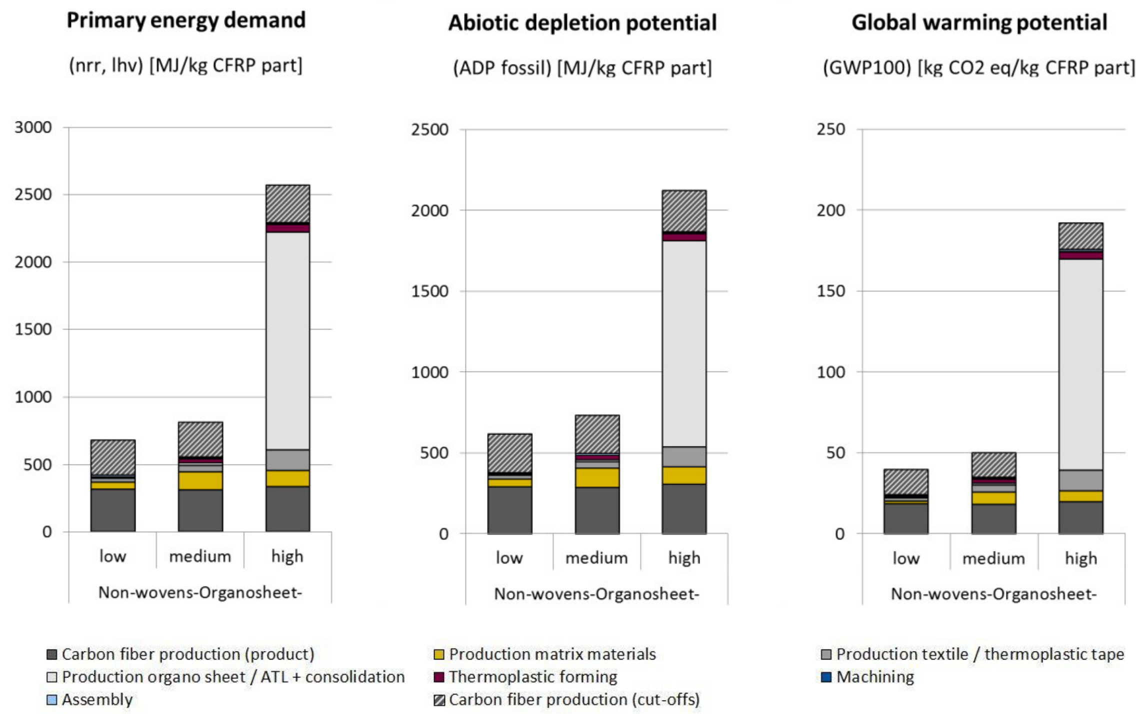
- PED between -17% and 217%
- ADP between -16% and 190%
- GWP between -21% and 283%

For a medium process energy setup, the carbon fiber production (w/o cut-offs) has a share of around 36 to 39% in each impact category, which decreases to 10 to 14% for a high process energy production setup.

The main driver is the impact of the organosheet production and consolidation, which increases by a factor of 100 between the medium and high setup. Overall, this leads to a strongly increased share of the processing technologies of

- 72% compared to 14% of PED
- 69% compared to 12% of ADP
- 78% compared to 18% of GWP

of the medium production setup. The LCIA results in other investigated impact categories exhibit the same tendency.



5.9 TP-AFP-consolidation-TP-forming process chain

The use of an AFP process enables a load path adapted design and a near net shape placement of thermoplastic sheets. For small production series, placement technology enabling 3D layup in combination with a direct consolidation might be the most efficient choice. However, for complex geometries impeding a 3D layup as well as for medium to large scale production, a faster 2D layup is often preferred. This implies a subsequent consolidation to ensure a homogenous heating-up before forming and a defined crystallization. The consolidation can be realized in a double-belt press or a continuous compression molding machine. The forming is similar to the organosheet process chain. The sheet is trimmed to the required shape and heated up to the melting temperature. The forming takes place in a self-heated tooling in a press ensuring a defined crystallization. In a small-scale production also variotherm consolidation and forming in an oven or press is possible. For the manufacturing of thermoplastic tows, the impregnation of continuous spread fibers with an extruded thermoplastic matrix in a continuous compression molding machine as well as a subsequent slitting process was considered.

Results of the OFAT energy analysis
In the best case an 80% reduction, worst case a 1470% increase of the process energy demand compared to the medium production setup was calculated.

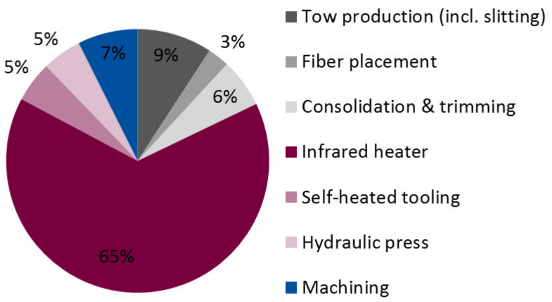
Main influencing parameters are:

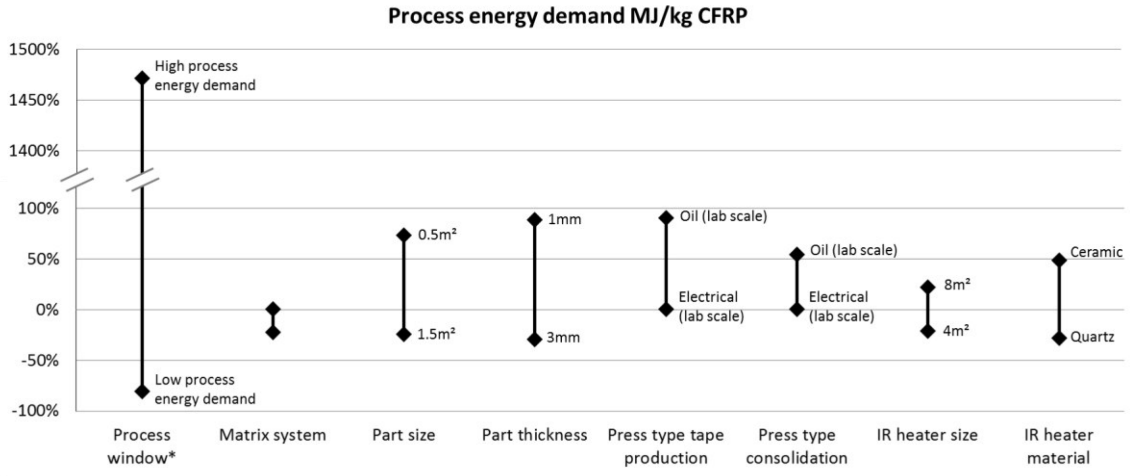
- Press type
- Part size and thickness
- IR heater size and material

Optimization potential
As the data for heating presses are gained only in lab scale, no reliable statements can be made. Furthermore, the part size and thickness are usually fixed in a production series. However, one potential point for optimization is the adaption of the IR heater to the part size.

Share of process steps
Dominating consumer for a medium production setup is the IR heater, mainly caused by the areal utilization rate. A 6 m² heating area for a 1 m² part is assumed.

All varied parameters and made assumptions are listed in Table 45 in appendix C.2.



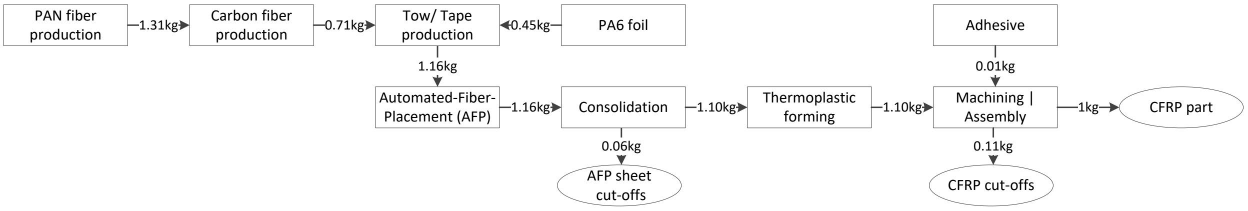


* Combining all parameters, which are leading to a low and to a high process energy demand

TP-AFP-consolidation-TP-forming process chain

Material flow

Due to the near net shape layup less cut-offs for trimming the consolidated sheet to the required shape are necessary. For the evaluation, an average cut-off of 5% is assumed. Possible cut-offs during tow production and any tow residuals on the spools are neglected. 10% cuttings during machining are considered. A detailed overview of all parameters relevant for the material flow and the process energy demand is given in Table 45 in appendix C.2.



Life cycle impact assessment

The production setup itself (except assembly) and the corresponding process energy demand have an impact on the results across all indicators. Deviating from the medium setup leads to a

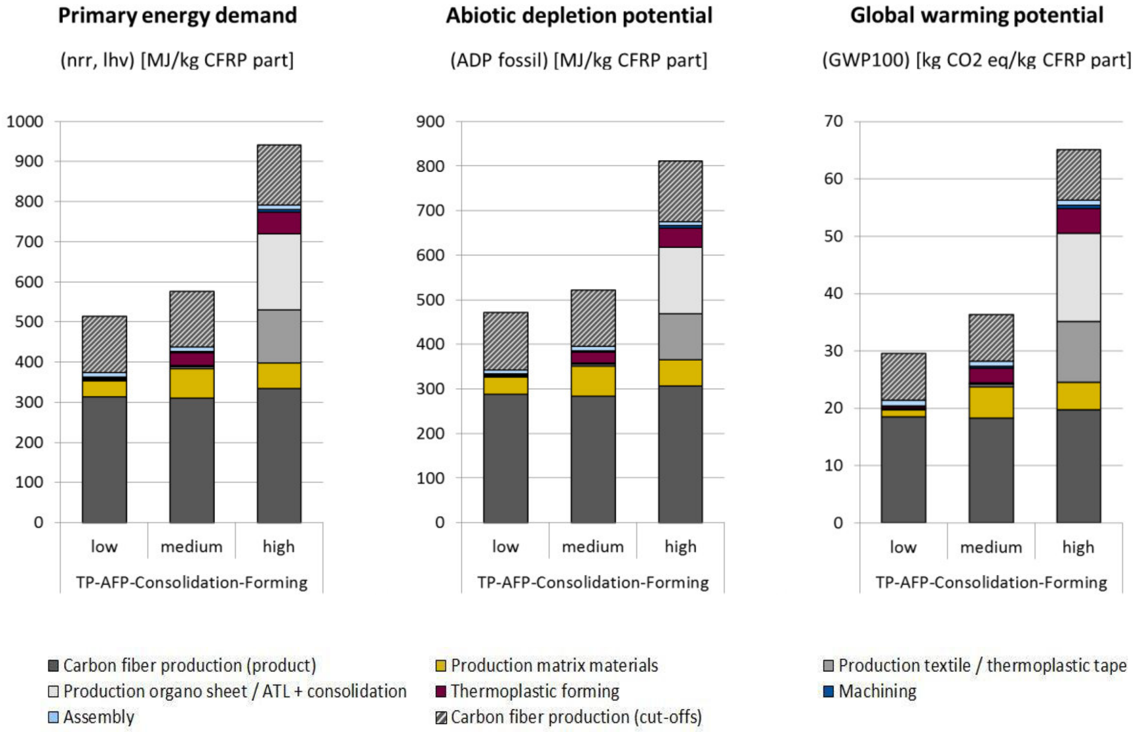
- PED between -11% and 63%
- ADP between -10% and 56%
- GWP between -19% and 79%

For a medium process energy setup, the carbon fiber production (w/o cut-offs) has a share of around 50 to 54% in each impact category, which decreases to 30 to 38% for a high process energy production setup.

The main driver is the impact of the AFP sheet production and consolidation, which increases by a factor of 50 between the medium and high setup. Overall, this leads to a strongly increased share of the processing technologies of

- 42% compared to 10% of PED
- 38% compared to 8% of ADP
- 49% compared to 12% of GWP

of the medium production setup. The LCIA results in other investigated impact categories exhibit the same tendency.


Primary energy demand

(nrr, lhv) [MJ/kg CFRP part]

Abiotic depletion potential

(ADP fossil) [MJ/kg CFRP part]

Global warming potential

(GWP100) [kg CO2 eq/kg CFRP part]

5.10 TP-ATL-consolidation-TP-forming process chain

Thermoplastic automated tape laying technologies combine the advantages of fiber placement processes and a standard organosheet production. High production volumes with low material cut-offs can be realized. However, similar to the fiber placement, a subsequent consolidation is necessary to ensure a homogenous heating-up before forming and a defined crystallization. The consolidation can be realized in a double-belt press or a continuous compression molding machine. The forming is similar to the organosheet process chain. The sheet is trimmed to the required shape and heated up to the melting temperature. The forming takes place in a self-heated tooling ensuring a defined crystallization. In a small-scale production also variotherm consolidation and forming in an oven or press is possible. For the manufacturing of thermoplastic tapes, the impregnation of continuous spread fibers with an extruded thermoplastic matrix in a continuous compression molding machine as well as a subsequent slitting process was considered.

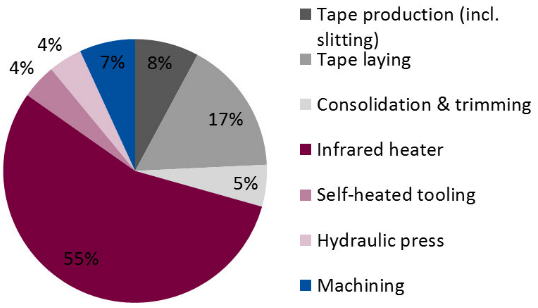
Results of the OFAT energy analysis
Combining all parameters leading to a low process energy demand results in 80% reduction, whereas the worst-case scenario leads to a 1300% increase compared to the medium production setup.

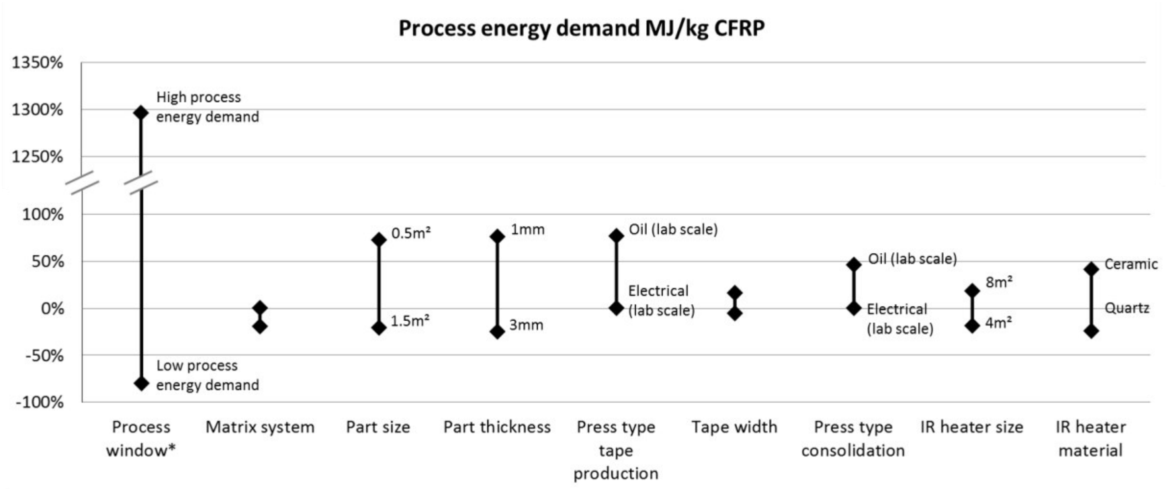
Main influencing parameters are:
- Press type
- Part size and thickness
- IR heater size and material

Optimization potential
As the data for heating presses are gained only in lab scale, no reliable statements can be made. Furthermore, the part size and thickness are usually fixed in a production series. However, one potential point for optimization is an adapted IR heater size and material.

Share of process steps
Dominating consumers for a medium production setup are the tape layup and the IR heater. The latter is mainly caused by the areal utilization rate, whereas a 6 m² heating area for a 1 m² part is assumed.

All varied parameters are listed in appendix C.2.



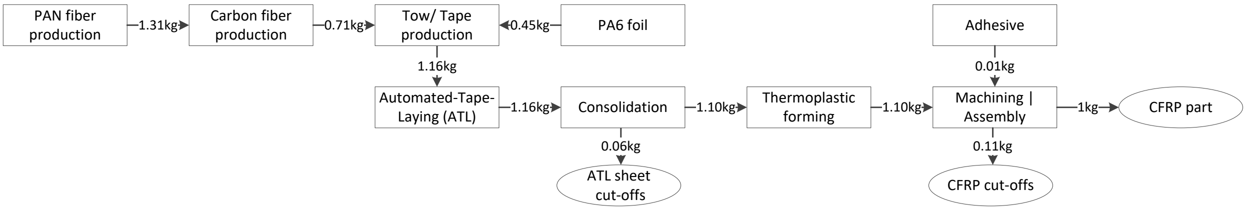


* Combining all parameters, which are leading to a low and to a high process energy demand

TP-ATL-consolidation-TP-forming process chain

Material flow

The near net shape layup causes lower cut-offs for trimming the consolidated sheet to the required shape. For the evaluation, an average cut-off of 5% is assumed. Possible cut-offs during tape production and any tow residuals on the spools are neglected. 10% cuttings during machining are considered. A detailed overview of all parameters relevant for the material flow and the process energy demand is given in Table 46 in the appendix C.2.



Life cycle impact assessment

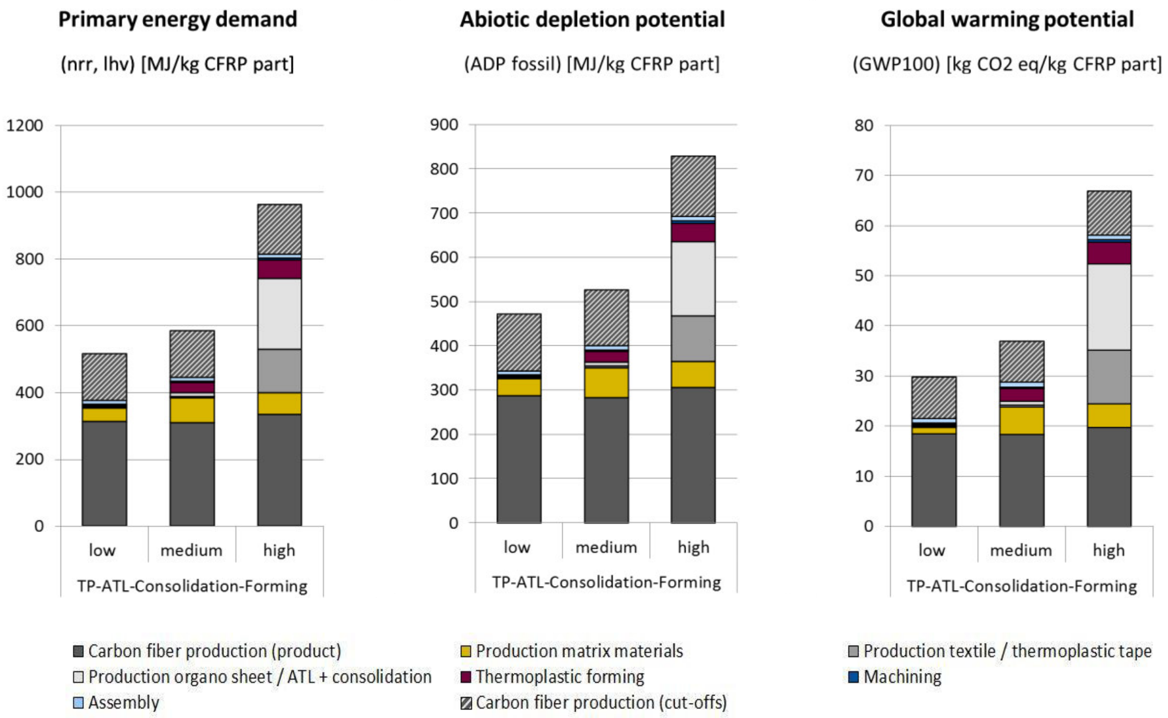
The production setup itself (except assembly) and the corresponding process energy demand have an impact on the results across all indicators. Deviating from the medium setup leads to a

- PED between -12% and 65%
- ADP between -10% and 57%
- GWP between -19% and 81%

For a medium process energy setup, the carbon fiber production (w/o cut-offs) has a share of around 50 to 54% in each impact category, which decreases to 29 to 37% for a high process energy production setup. The main driver is the impact of the ATL sheet production and consolidation, which increases by a factor of 50 between the medium and high setup. Overall, this leads to a strongly increased share of the processing technologies of

- 43% compared to 11% of PED
- 40% compared to 9% of ADP
- 50% compared to 14% of GWP

of the medium production setup. The LCIA results in other investigated impact categories exhibit the same tendency.



6 Impact of production related measures on the environment

In this chapter, exemplary CFRP parts are in the focus from an environmental perspective. While chapter 5 focuses on specific factors influencing the energy demand for transforming carbon fiber and matrix materials into a CFRP part, chapter 6 focusses slightly less into the details of processing technologies and instead takes a top-down perspective at the life cycles of various CFRP parts. Not the technical parameters of singular processes are varied, but entire supply chains. In conjunction with the detailed analysis of processing technologies in chapter 5, chapter 6 gives the reader an as-complete-as-possible view of the kinds of leverage for environmental optimization of CFRP part production.

Three kinds of leverage over the environmental impacts of CFRP parts are explored: First, the influence of material efficiency in the production of CFRP parts from CF and matrix materials (chapter 6.1). Second, this chapter deals with the influence of the boundary conditions under which the manufacturing parameters for CFRP parts are to be optimized (6.2). Third, multiple scenarios into variants, to demonstrate the combined leverage that can be raised if CFRP value chains are consciously optimized; including implications on the use phase (chapter 6.3).

In all cases, the entire supply chain of each CFRP part is investigated. This includes the provision of resources such as crude oil for PAN as a CF precursor, as well as for matrix materials, the provision of PAN and subsequently PAN fiber, carbonization, spinning, and finally processing into a finished CFRP part. The use phase is considered through generic fuel reduction values (FRV), representing fuel savings relative to a (heavier) reference design. Furthermore, the variants of CFRP parts are compared among each other.

6.1 Impact of various material-efficient processing technologies

To investigate the influence of advanced processing technologies from a life cycle point of view, alternative cases for the production of carbon fibers are defined. For every case, the applied processing technologies are varied while all other properties are fixed to the medium value introduced in chapter 5. Thermoset and thermoplastic CFRPs are analyzed separately. The impact categories primary energy demand, global warming potential and abiotic resources depletion are discussed in detail. The LCIA results in other investigated impact categories exhibit the same tendency.

Thermoset based CFRP

For thermoset matrix materials the modeled technologies range from NCF-RTM, DFP-RTM, TFP-RTM, Braiding-RTM, to two different pultrusion processes (epoxy and polyurethane matrix). The entire process chain spans from carbon fiber production, matrix materials and textile product fabrication to injection/curing, as well as finishing and assembly of the final product. CF production is further broken down into the fraction that stays in the product and the fraction that ends up in cut-offs. Recycling of the cut-offs is not considered in either case.

Figure 5 shows the comparison of the GWP per produced kilogram of CFRP for six different material-efficient processing technologies. The total GWP for NCF-RTM medium as reference is just below 39 kg CO_2eq/kg, of which the single biggest share is caused by the carbon fiber production. The share of CF that remains in the product causes 18 kg CO_2eq/kg, and the CF share that ends up in the cut-off another 13 kg CO_2eq/kg. In sum, CF production relates to 79% of the total GWP. Matrix material provision and injection/curing jointly contribute 5.6 kg CO_2eq/kg (14%) to the total GWP. Production of textile product, preforming, assembly, and finishing are minor contributors.

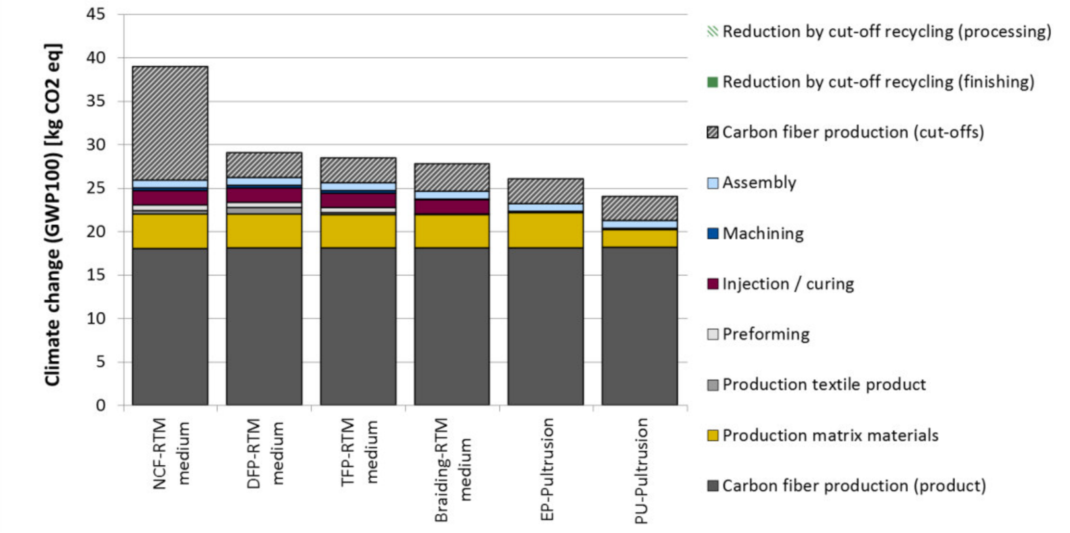


Figure 5: Climate change (GWP 100) comparison of thermoset CFRP manufacturing technologies for the production of 1 kg thermoset-based CFRP

Both CF production and part assembly are identical across all cases presented in Figure 5, but notable differences occur in the other processes. The decrease of overall GWP is realized mostly through a significant reduction of the cut-off. Less CF wasted as cut-off translates into less GWP for CF provision for the finished CFRP part. The GWP of the CF in the cut-offs is reduced to 2.8 to 3.2 kg CO_2eq/kg in DFP-RTM, TFP-RTM, Braiding-RTM and both pultrusion cases - a relative improvement of around 26% in GWP.

As for the matrix materials, negligible differences occur between the RTM technologies. EP-pultrusion causes a marginally higher GWP, whereas PU-pultrusion reduces the GWP of matrix material by more than one quarter compared NCF-RTM medium (-1.9 CO_2eq/kg, or -5% of the total GWP).

The GWP share of machining is the same for NCF-RTM, DFP-RTM and TFP-RTM (0.27 kg CO_2eq/kg), but is significantly lower for Braiding-RTM (0.04 kg CO_2eq/kg). For pultrusion with either EP or PU requires no machining at all. Pultrusion also does away with the production of an intermediate textile product and preforming. Consequently, textile production, preforming and machining show no impact in the environmental profile of a pultruded CFRP part, resulting in 1.4 kg CO_2eq/kg less GWP (-3% compared to NCF-RTM medium).

Figure 6 shows the potential reduction of GWP per manufacturing technology compared to the medium production setup of the NCF-RTM process chain (NCF-RTM medium). For the material-efficient production technologies, reductions of 27 up to 40% can be achieved. Pultrusion offers a greater advantage than RTM, with polyurethane being the favorable matrix material for pultrusion (from an environmental point of view).

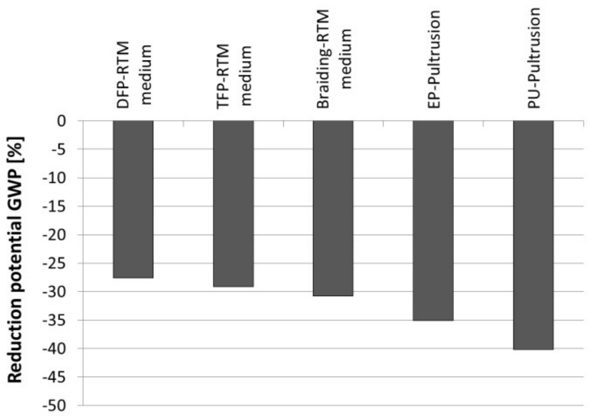


Figure 6: GWP reduction potential s per manufacturing technology for the production of 1 kg thermos et-based CFRP

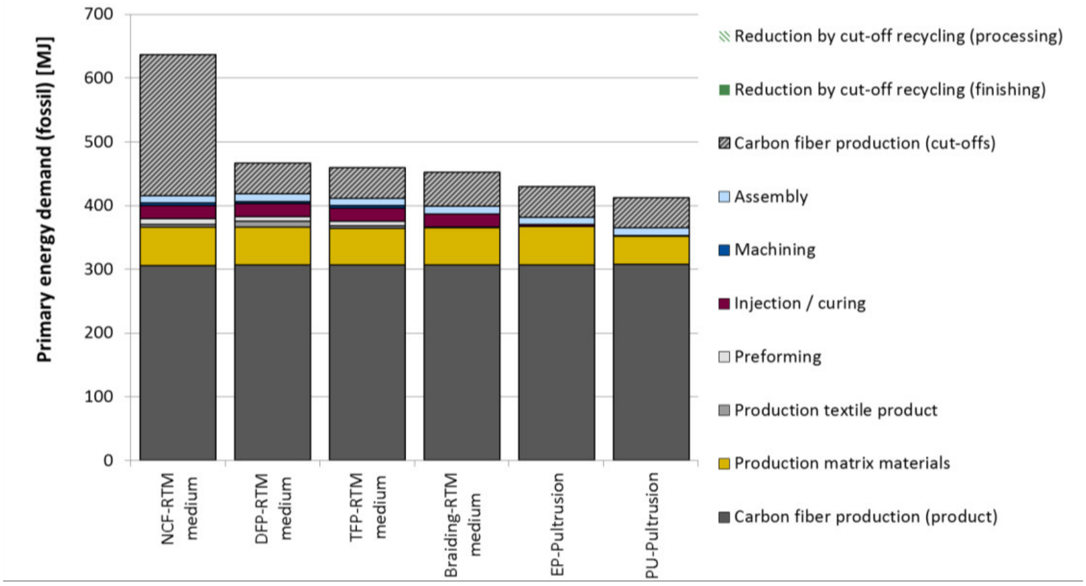


Figure 7: PED comparison of thermoset CFRP manufacturing technologies

Non-renewable primary energy demand and fossil abiotic resource depletion behave similar to GWP (see Figure 7 and Figure 8). The specific numbers differ, but the overall trend is the same. All examined technologies allow significantly lower cut-off rates, which is the single biggest advantage over the NCF-RTM process chain (up to 27% less PED and ADP). Pultrusion does away with textile production, preforming, and machining, saving another 2.4 to 2.7% of the total PED and ADP. PU offers both lower PED and ADP than EP as a matrix material in a pultruded CFRP part.

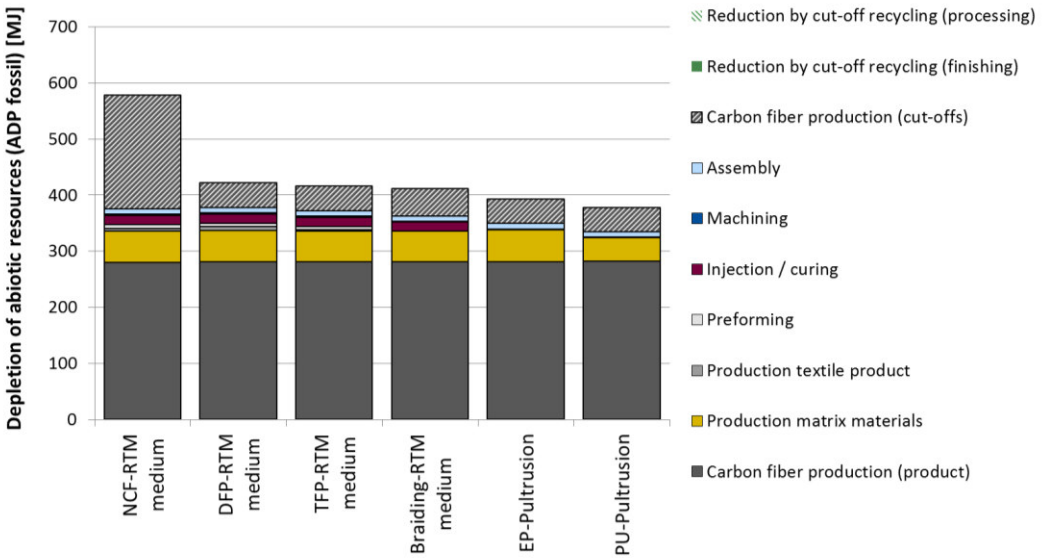


Figure 8: ADP comparison of thermoset CFRP manufacturing technologies

Thermoplastic based CFRP

Three different cases of thermoplastic-based CFRP are examined and compared. The reference case represents a part manufactured via organosheet production with medium energy efficiency and medium cut-off. This is contrasted with two automated placement techniques: The first one is automated tape laying (TP-ATL), the second one automated fiber placement (TP-AFP). The matrix material is PA6 in all cases. The entire process chain spans from carbon fiber production, matrix materials and textile product fabrication to forming, as well as finishing and assembly of the final product. CF production is further broken down into the fraction that stays in the product and the fraction that ends up in cut-offs. Recycling of the cut-offs is not considered in either case.

Figure 9 shows the comparison of the global warming potential per produced kilogram of CFPR part for the organosheet medium route, and the two automated placement technologies. The total GWP for the organosheet production route with a medium setup is 54.5 kg CO_2eq/kg, of which the single biggest share is caused by the carbon fiber production. The share of CF that remains in the product causes 22.5 kg CO_2eq/kg and the CF share that ends up in the cut-off another 19.2 kg CO_2eq/kg. In sum, CF production relates to 77% of the total GWP. The provision of the matrix material contributes 6.9 kg CO_2eq/kg (13%) to the total GWP, and the forming step another 2.5 kg CO_2eq/kg (5%). Production of textile product, of the organosheet, machining, and assembly are minor contributors.

Both of the two automated placement techniques allow significantly less cut-off, which accounts for the single largest contribution to the decreased GWP in comparison to the organosheet process chain. As for the thermoset-based CFRP, less CF wasted as cut-off translates into less GWP for CF provision for the finished CFRP part. The GWP of the CF in the cut-off is reduced to 8.2 kg CO_2eq/kg (down from 19.2 kg CO_2eq/kg, a reduction of more than 25% of the total GWP of the organosheet process chain).

ATL and AFP require less matrix material, due to the reduced tow/tape cut-offs. The GWP contribution from the matrix provision is thus reduced by another 1.5 kg CO_2eq/kg (2.7% of the total organosheet GWP). The production of the tape for ATL/AFP is associated with a lower GWP (0.39 kg CO_2eq/kg) than the textile production for the organosheet (0.75 kg CO_2eq/kg). While this is representing a 48% difference between the individual process steps, it amounts to less than 1% in the scope of the entire process chain. Thermoplastic forming, machining, and assembly are not affected. Both ATL and AFP show a reduction potential of 32 and 33%, respectively. As described above, the main advantage of these automated placement technologies is the significantly lower cut-off rate. Other differences are small.

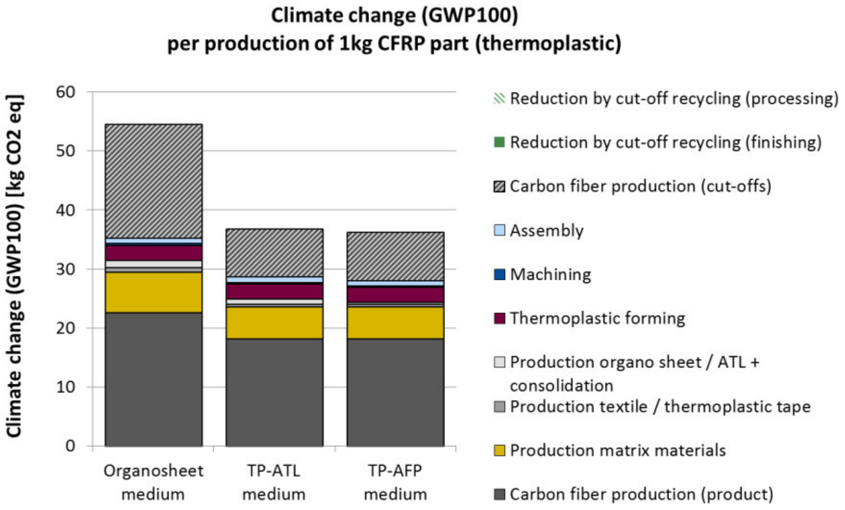


Figure 9: Climate change (GWP 100) comparison of thermoplastic CFRP manufacturing technologies for the production of 1 kg thermoplastic-based CFRP

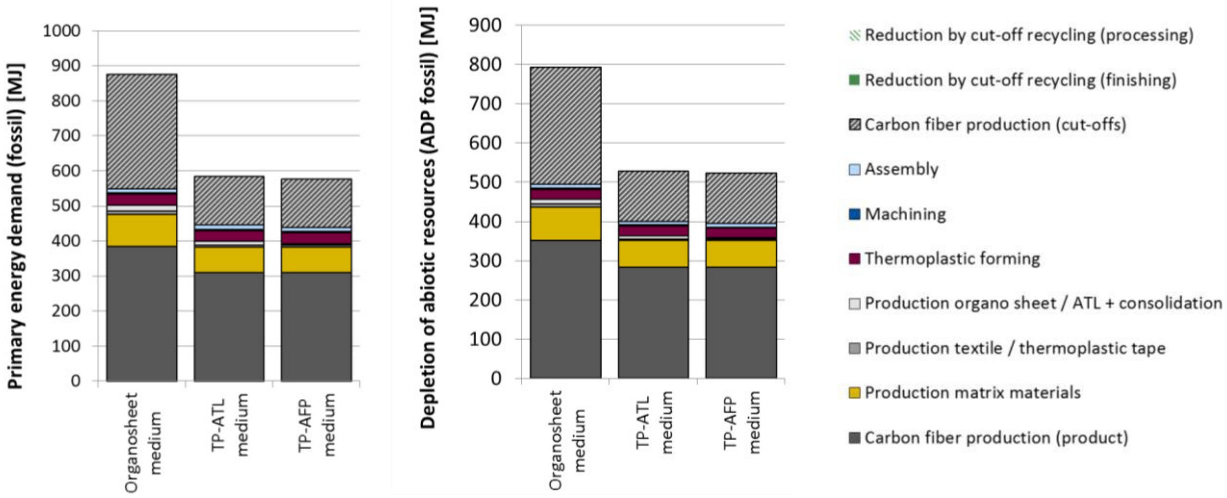


Figure 10: PED and ADP comparison of thermoplastic CFRP manufacturing technologies

Non-renewable primary energy demand and fossil abiotic resource depletion behave similar to GWP (see Figure 10). The specific numbers differ, but the overall trend is the same. Both examined technologies allow much lower cut-off rates, which is the single biggest advantage over organosheet medium (up to 34% less PED and ADP).

6.2 Analysis of part-related parameters

In the following sections, the influence of a CFRP part's geometry on its environmental profile is examined. The exemplary CRFP part is either a curved surface or a profile. Variable parameters, see Table 8, are the surface area of the part, its thickness, and the fiber volume content, whereas all other properties are fixed to a representative medium value (see chapter 5). The results are compared across the defined cases. Note that the functional unit is 1 kg part mass, not 1 part. Thermosets and thermoplastics are investigated separately in the impact categories primary energy demand, global warming potential and abiotic resources depletion.

Thermoset based CFRP

For thermoset matrix materials the entire process chain spans from carbon fiber production, matrix materials and textile product fabrication to injection/curing, as well as finishing and assembly of the final product. CF production is further broken down into the fraction that stays in the product and the fraction that ends up in cut-offs. Recycling of the cut-offs is not considered in either case.

Figure 11 shows the comparison of the global warming potential per produced kilogram of CFPR part for six different part geometries. The total GWP for the medium sized part is just below 39 kg CO_2eq/kg, of which the single biggest share is caused by the carbon fiber production. The share of CF that remains in the product causes 18 kg CO_2eq/kg, and the CF share that ends up in the cut-off another 13 kg CO_2eq/kg. In sum, CF production relates to 79% of the total GWP. Matrix material provision and injection/curing jointly contribute 5.6 kg CO_2eq/kg (14%) to the total GWP. Production of textile product, preforming, assembly, and finishing are minor contributors.

Table 8: Varied part parameters

	Large and thick	Medium	Small and thin	Unit
Part size/ diameter	1.5 (ø 150 mm)	1 (ø 92.5 mm)	0.5 (ø 35 mm)	m²
Part thickness	3	2	1	mm
Fiber volume content	45	50	55	%

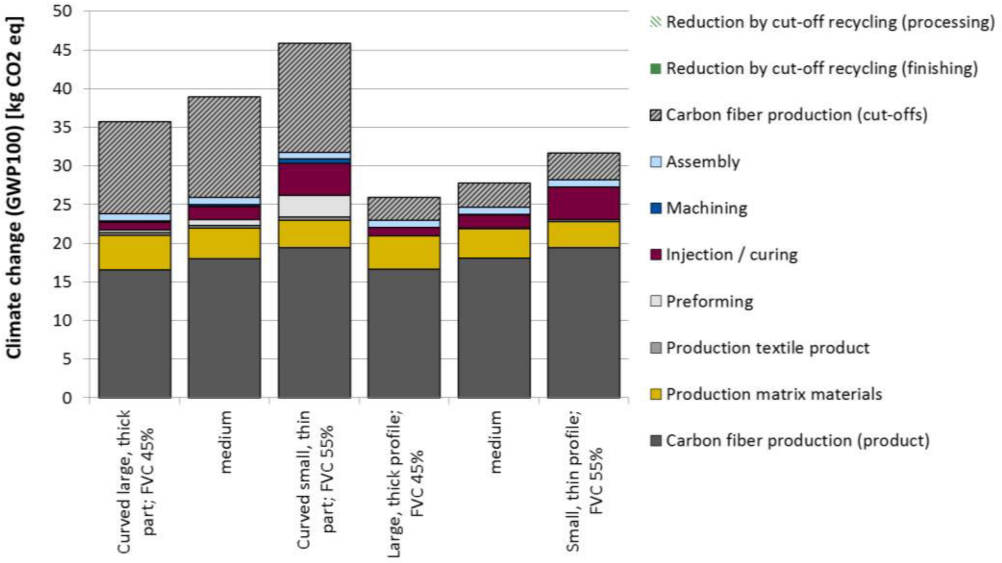


Figure 11: GWP comparison of thermoset CFRP geometries for the production of 1 kg thermoset-based CFRP

In general, large parts entail a lower GWP per 1 kg part than small parts, thick parts a lower GWP than thin parts, and a lower FVC also entails a lower GWP than a higher FVC. This is valid for curved surface and profile parts. The differences are more pronounced for curved surface parts, though.

These effects are superimposed on each other. The most relevant driver of a CFRP part's GWP is the provision of the carbon fiber, which is dictated by the fiber volume content and the cut-off rate.

Thermoplastic based CFRP

Only parts with a curved surface geometry are examined with a thermoplastic matrix. The entire process chain spans from carbon fiber production, matrix materials and textile product fabrication to injection, as well as finishing and assembly of the final product. CF production is further broken down into the fraction that stays in the product and the fraction that ends up in cut-offs. Recycling of the cut-offs is not considered in either case.

Figure 12 shows the comparison of the global warming potential per produced kilogram of CFPR part for the medium sized part and two other part geometries. The total GWP for the medium part is 54.5 kg CO_2eq/kg, of which the single biggest share is caused by the carbon fiber production. The share of CF that remains in the product causes 22.5 kg CO_2eq/kg, and the CF share that ends up in the cut-off another 19.2 kg CO_2eq/kg. In sum, CF production relates to 77% of the total GWP. The provision of the matrix material contributes 6.9 kg CO_2eq/kg (13%) to the total GWP, and the forming step another 2.5 kg CO_2eq/kg (5%). Production of textile product, of the organosheet, machining, and assembly are minor contributors.

In general, large parts entail a lower GWP per 1 kg part than small parts, thick parts a lower GWP than thin parts, and a lower FVC also entails a lower GWP than a higher FVC. The most relevant driver of a CFRP part's GWP is the provision of the carbon fiber, which is dictated by the fiber volume content and the cut-off rate.

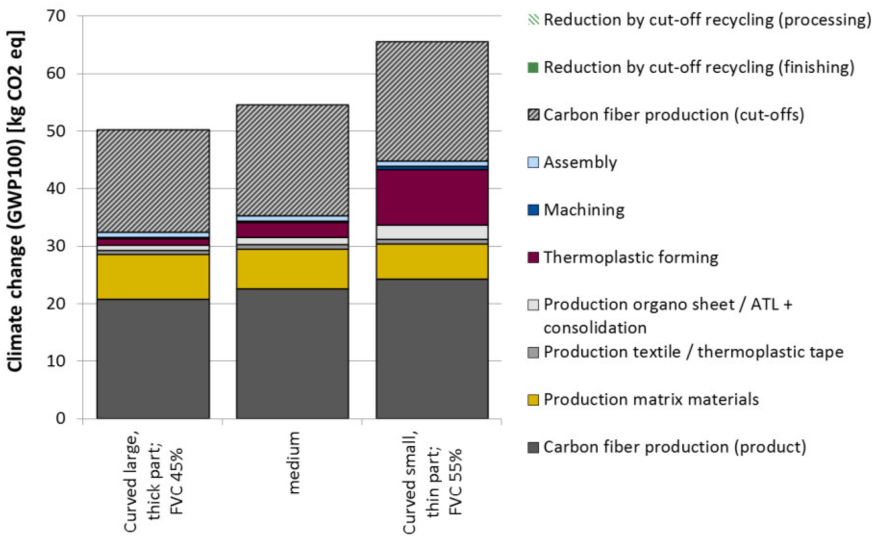


Figure 12: GWP comparison of thermoplastic CFRP geometries for the production of 1 kg thermoplastic-based CFRP

6.3 Analysis of different optimization measures

In this section the reduction potential of various measures regarding the environmental impact is investigated. Each scenario in Figure 13 represents a singular improvement option in the process chain of a CFRP part. Several scenarios are combined into variants, to show both singular and combined effects. However, the combined effect is not simply the sum of the singular effects.

All cases in chapter 6.3 are compared to a base case called variant 1 (or simply V1). This is an exemplary CFRP part, with either thermoset or thermoplastic matrix, of medium size thickness, and with medium fiber volume content. It is assumed that the CF precursor PAN fiber is produced in Japan, using the average Japanese electricity grid mix. The carbon fiber itself is assumed to be produced in various

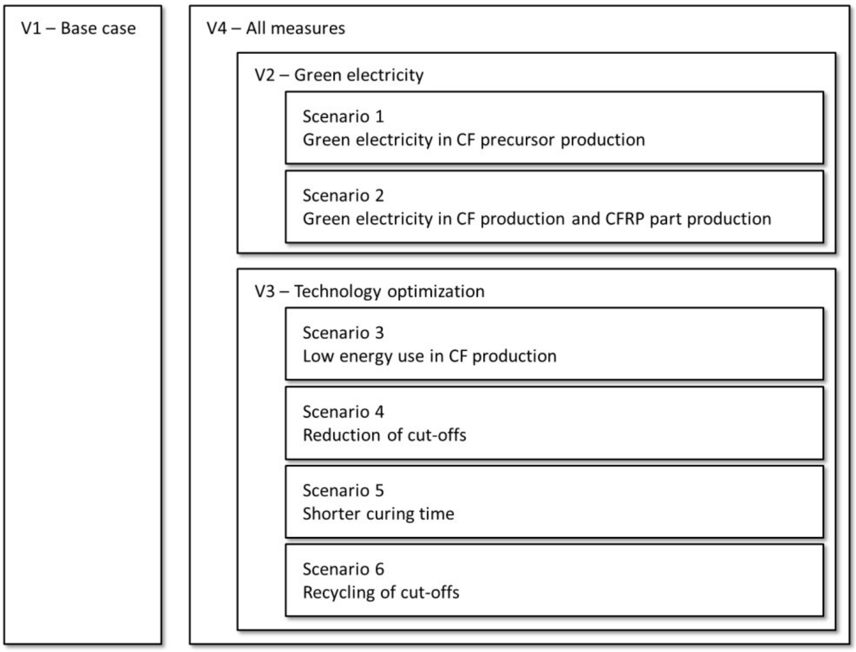


Figure 13: Overview of the investigated measures to reduce the environmental burden

countries that dominate the world market for CF, using a weighted average of the respective national grid mixes. The matrix material is assumed to be either epoxy (thermoset) or PA6 (thermoplastic). The production of the CFRP part from CF and the respective matrix material is assumed to take place in Germany, using the average German electricity grid mix. The specific assumptions for the material manufacturing are documented in Table 7 at page 28. The specific production parameters for the process chains are given in the appendix C.3.

In addition to energy and technology based measures also the impact of an optizimed structure design of carbon fiber reinforced thermosets is analyzed. For each variant in Figure 13 two to three different weight reduction possibilites and their influence on the environmental burden is investigated.

In this regard, the weight reduction leads to two different effects. On the one hand the environmental burden of the production phase will be reduced as less material is required for the same function. On the other hand for conventional combustion engines less petrol or diesel is required and lower emission are released in the use phase. All relevant boundary conditions to evaluate the environment reduction potential in the use phase is explained in chapter 3. In this section only the results will be presented.

Thermoset based CFRP

In Figure 14 the calculated GWP for each scenario and variant is illustrated. In Figure 15 the achieved reduction potential compared to the base case V1 is quantified. It is viewable, that the total GWP for V2 is significantly lower than for V1, at 22.2 kg CO_2eq/kg. Relative to V1, this is a reduction by almost 45%. Green electricity in precursor production (scenario 1) reduces the GWP by 2.0 kg CO_2eq/kg (5% relative to V1). Green electricity in carbon fiber and part production (scenario 2) reduces the GWP by 15.9 kg CO_2eq/kg, almost 40%. The production of carbon fiber from PAN fiber requires a lot of electricity, so the switch to green electricity translates into the strong reduction of the GWP per 1 kg CFRP part (around 27.5% relative to V1). Production of textile product, preforming, injection/curing, assembly, and finishing allow a collective GWP reduction of 4.9 kg CO_2eq/kg by switching to green electricity provision for these steps. The provision of the matrix material is not affected.

The total GWP for V3 is slightly lower than that for V2, at 21.6 kg CO_2eq/kg. Relative to V1, this is a reduction by slightly over 46%. The most effective measures are those targeting the production and efficient use of carbon fiber.

Optimization of energy use in CF production (scenario 3) saves 9.1 kg CO_2eq/kg (22% relative to V1). Reduction of cut-offs (scenario 4) saves practically the same amount of GHG emissions (10.1 kg CO_2eq/kg). Reduction of curing times (scenario 5) reduces the GWP by 1.2 kg CO_2eq/kg (3%). Recycling of cut-offs (scenario 6) is more effective, allowing a GWP reduction of 3.0 kg CO_2eq/kg (7.5% relative to V1). Please mind that the green-striped segment of the column in Scenario 6 in Figure 14 is saved by recycling as much as possible of the cut-offs, both from processing and from finishing.

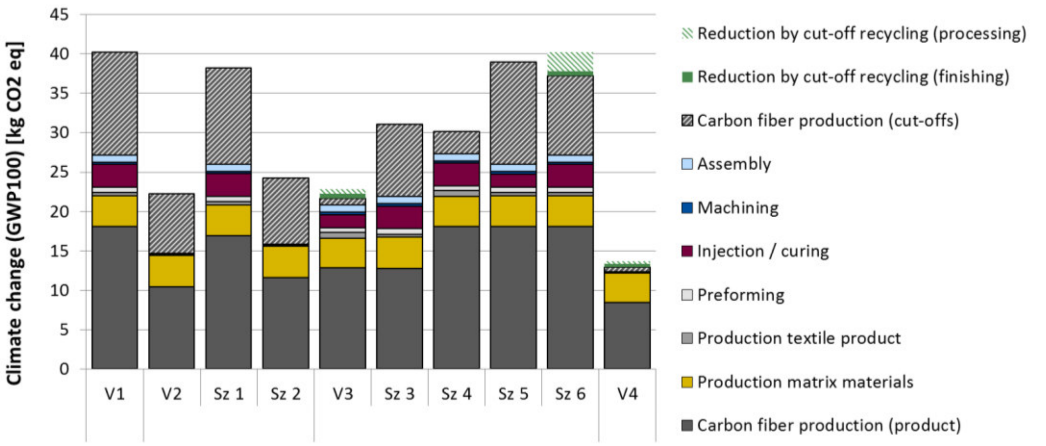


Figure 14: GWP comparison of scenarios and variants for thermoset CFRP parts for the production of 1 kg thermoset-based CFRP

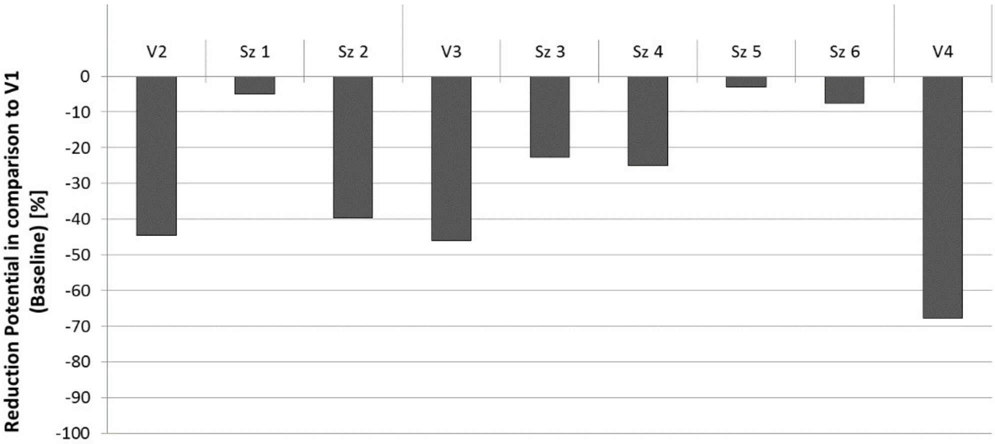


Figure 15: GWP reduction comparison of scenarios and variants for thermoset CFRP parts

Both V2 (green electricity) and V3 (technology improvement) cut the GWP of a CFRP part in half. Combining all measures into V4 brings the GWP of 1 kg CFRP part down to less than 13 kg CO_2eq/kg. As mentioned above, the effects do not combine in a linear fashion. Yet the V4 results represent a 40% decrease from the GWP of V3, a 47% decrease from V2, and a 68% decrease from V1.

The other indicators (PED non-renewable, ADP fossil) behave similarly to GWP in this analysis. The major contribution to either category is the provision of carbon fiber. Accordingly, those measures that either limit the wasteful use of CF or decrease the environmental burden of CF production are most effective at decreasing the environmental burden of a CFRP part. V2 and V3 reduce the PED by 38% and 46%, and reduce the ADP by 34% and 48%, respectively. Combining all measures into V4 allows a reduction of the PED by 64% and of the ADP by 62%.

Thermoplastic based CFRP

The optimization potential for thermoplastic based CFRP production is illustrated in Figure 16 and Figure 17. The total GWP for V2 is significantly lower than for V1, at 31.3 kg CO_2eq/kg. Relative to V1, this is a reduction by over 42%. Green electricity in precursor production (scenario 1) reduces the GWP by 2.7 kg CO_2eq/kg (5% relative to V1). Green electricity in carbon fiber and part production (scenario 2) reduces the GWP by 20.5 kg CO_2eq/kg, more than 37%. The production of carbon fiber from PAN fiber requires a lot of electricity, so the switch to green electricity translates into the strong reduction of the GWP per 1 kg CFRP part (around 27%). Production of organosheet, thermoplastic forming, assembly, and finishing allow a collective GWP reduction of 5.6 kg CO_2eq/kg by

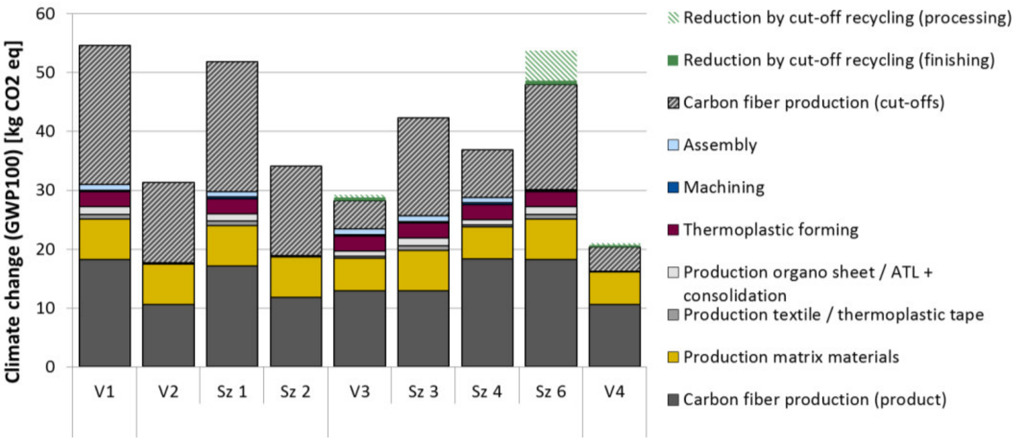


Figure 16: GWP comparison of scenarios and variants for thermoplastic CFRP parts for the production of 1 kg thermoplastic based CFRP

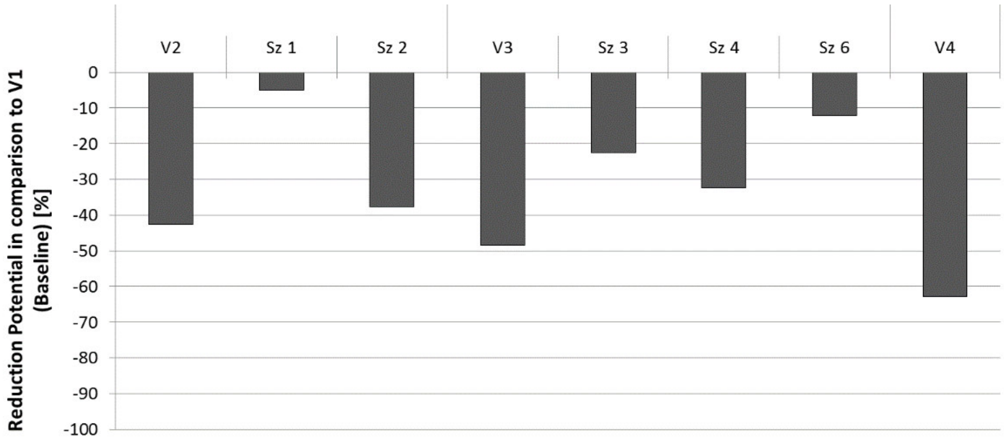


Figure 17: GWP reduction comparison of scenarios and variants for thermoplastic CFRP parts

switching to green electricity provision for these steps. The provision of the matrix material is not affected. The total GWP for V3 is slightly lower than that for V2, at 28.2 kg CO_2eq/kg. Relative to V1, this is a reduction by slightly over 48%. The most effective measures are those targeting the production and efficient use of carbon fiber. Optimization of energy use in CF production (scenario 3) saves 12.2 kg CO_2eq/kg (22% relative to V1). Reduction of cut-offs (scenario 4) saves more GHG emissions (17.7 kg CO_2eq/kg, or 32%). Recycling of cut-offs (scenario 6) is also effective, allowing a GWP reduction of 6.6 kg CO_2eq/kg (12% relative to V1). Please mind that the green-striped segment of the column Scenario 6 in Figure 16 is saved by recycling as much as possible of the cut-offs, both from processing and from finishing.

Both V2 (green electricity) and V3 (technology improvement) cut the GWP of a CFRP part by more than 40%. Combining all measures into V4 brings the GWP of 1 kg CFRP part down to only 20.3 kg CO_2eq/kg. As mentioned above, the effects do not combine in a linear fashion. Yet the V4 results represent a 28% decrease from the GWP of V3, a 35% decrease from V2, and a 63% decrease from V1.

The other indicators (PED non-renewable, ADP fossil) behave similarly to GWP in this analysis. The major contribution to either category is the provision of carbon fiber. Accordingly, those measures that either limit the wasteful use of CF or decrease the environmental burden of CF production are most effective at decreasing the environmental burden of a CFRP part. V2 and V3 reduce the PED by 37 and 49%, and reduce the ADP by 33 and 48%, respectively. Combining all measures into V4 allows a reduction of the PED by 60% and a reduction of the ADP by 57%.

Reduction potentials of an optimized design for carbon fiber reinforced thermosets

To evaluate the impact of an optimal structure design, several weight reduction potentials are investigated. For V1 and V2 a weight reduction of 0 to 20% can be achieved depending on the part loads and the contributed effort in the design phase. For an isotropically loaded part and limited design (due to time schedule, costs or given installation space) a weight reduction potential of 0% is assumed. In contrast, a highly anisotropically loaded part with the possibility of an optimal design results in 20% weight savings compared to a quasi-isotropic conventional layup. V3 and V4 offer greater weight saving potentials due to the introduction of a material-efficient placement technology. In contrast to textiles with fixed fiber orientations, dry fiber placement technologies allow a load path adapted layup. Therefore, a maximum weight reduction of 30% is assumed. All weight reduction potentials are summarized in Table 9.

Table 9: Overview of possible weight reduction potentials due the loadings, design and preform technology

Weight reduction potential	0%	10%	20%	30%
Type of loadings	isotropic	anisotropic	anisotropic	anisotropic
	or	or	and	and
Optimal part design	no	yes	yes	yes
	and	and	and	and
Layup system enabling a load path design	no	no	no	yes

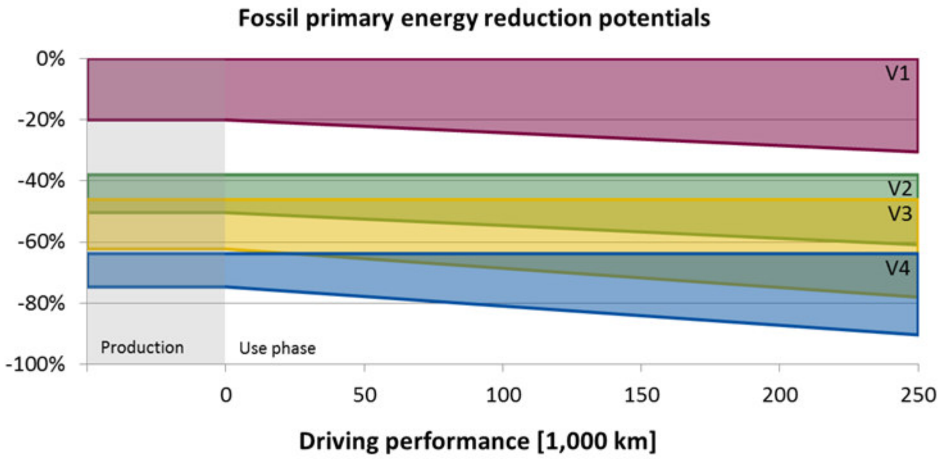


Figure 18: Impact of energy and technology related measures for different weight reduction potentials realized by an optimal structure design on the fossil primary energy demand

In Figure 18 for all four variants the possible reduction potentials regarding the non-renewable primary energy demand considering the discussed weight savings are shown. The 0% base line is identical to V1 without any weight savings.

The red area is the possible reduction potential, which can be achieved by weight savings of up to 20% and fuel savings of up to 035 l per 100 km and per 100 kg weight reduction. The green area in Figure 18 corresponds to the reduction potentials of V2. In addition to the use of renewable energy sources in the carbon fiber and part production (PED reduction 38 %), further savings can be achieved in the production phase due to an optimized design. However, both measures interact, and the individual saving potential cannot be summed up. In total, up to 50% of non-renewable primary energy can be saved in the production phase depending on the achieved weight reduction. Further savings in the use phase varies with the fuel type, the assumed fuel reduction value and the driving performance. V3 and V4 follow a similar trend to V1 and V2. However in the use phase greater savings are possible due to a load path adapted design.

Figure 18 indicates that the highest reduction potential are realized in the production phase. For a detailed analysis and quantification, the driving performance is fixed to 200,000 km and the achieved savings regarding the non-renewable primary energy demand the global warming potential are evaluated.

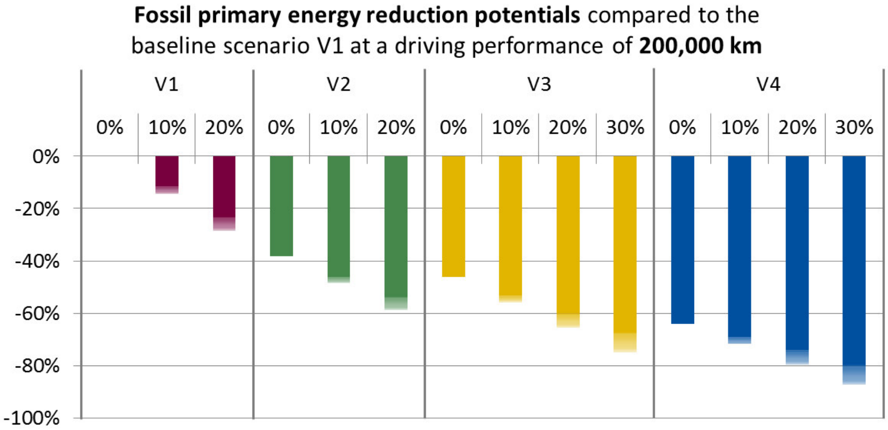


Figure 19: Fossil primary energy reduction potentials for different optimization measures for a fixed driving performance of 200,000 km

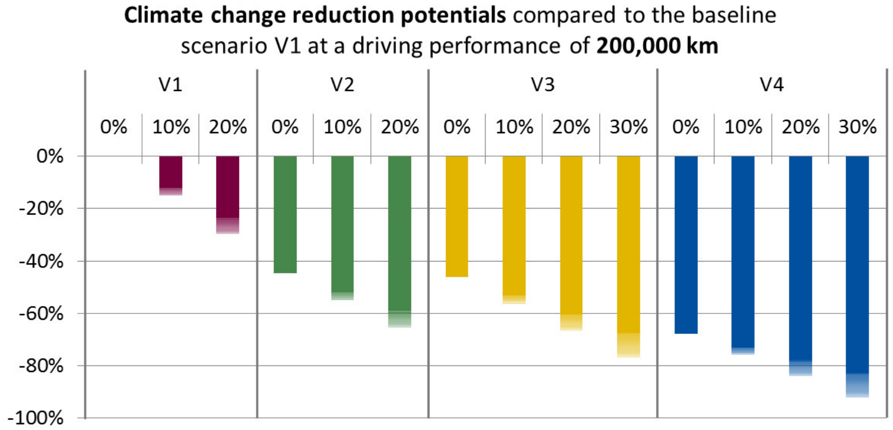


Figure 20: Climate change reduction potentials for different optimization measures for a fixed driving performance of 200,000 km

In Figure 19 and Figure 20 the reduction potential depending on the achieved weight savings for a fixed driving performance of 200,000 km is presented. The color gradient at the end of each column represents additional saving potentials. For example the use of gasoline results in a larger reduction compare to diesel. Furthermore if primary weight reductions of more than 100 kg are feasible, higher FRVs can be assumed due to secondary measures, e.g. adaption of the powertrain. In Table 10 all reduction potentials are summarized. In best case, a total reduction of primary energy demand combining all optimization measures of over 80% is possible.

Table 10: Summary of possible reduction potentials for a fixed driving performance of 200,000 km

Weight savings	**V1**	**V2**	**V3**	**V4**
Non-renewable primary energy demand				
0%	0%	38%	46%	64%
20%	23 to 28%	53 to 59%	60 to 65%	74 to 79%
30%	---	---	67 to 75%	79 to 87%
Global warming potential				
0%	0%	45%	46%	68%
20%	24 to 30%	59 to 66%	60 to 67%	78 to 84%
30%	---	---	68 to 77%	83 to 92%

7 Impact of production related measures on the product costs

In addition to the environmental footprint, the production costs, including material, manufacturing and labor costs, were analyzed. Engineering and development expenses are not considered. In addition to the parameters evaluated within the environmental analysis, the annual production quantity is varied. Since the utilization rate of the equipment is not fixed in this study, this also has an impact on the production costs. The most relevant assumptions can be taken from Table 11. All other parameters are listed in the appendix C.4.

Table 11: Main parameters for the base case 2012

Material costs	**Non-Crimp-Fabrics**	**Carbon fiber roving**	**Epoxy resin**
	50 €/kg	25 €/kg	6 €/kg
Part geometry	**Part size**	**Part thickness**	
Curved parts	0.5 m² to 1.5 m²	1 mm to 3 mm	
Profiles	Ø35 mm to Ø150 mm		
Production setup	**Preforming**	**Curing process**	**Cut-offs**
Curved parts	NCF-IR-press forming	RTM 5min	40% preforming| 10% machining
Profiles	Braiding	RTM 5min	5% preforming|10% machining
Plant availability	85%		
No. of shifts per day	3		

In Figure 21, the weight-specific costs for the defined scenarios in Table 11 are illustrated. With higher production volumes, the costs decrease. The main reason is the improved utilization rate of the equipment, which results in lower weight-specific manufacturing costs. However, significant cost reductions are visible up to 50,000 parts per year. Furthermore, at a specific part quantity the costs abruptly increase. Here the highest possible utilization rate is reached, and a multiplication of the equipment is required. The differences between curved parts and profiles are related to the process chain. Whereas for profiles a braiding process with 5% cut-offs is considered, curved parts are manufactured with standard textiles resulting in 40% cut-offs.

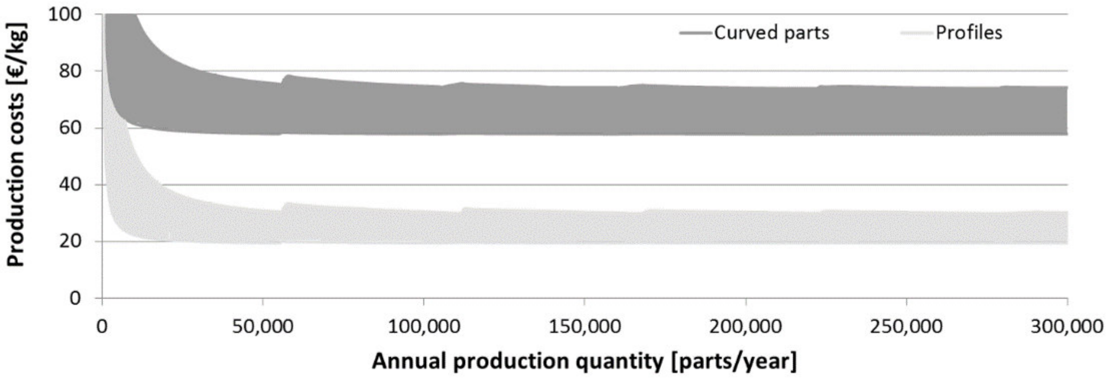


Figure 21: Manufacturing costs [€/kg] depending on the annual production quantity for the base case in 2012

7.1 Analysis of part-related parameters

The weight-specific production costs in Figure 21 indicate that the part-related parameters have an influence on the resulting costs. To quantify the impact, three characteristic production volumes are specified: 5,000 parts per year correspond to a small-scale, 75,000 to a medium and 300,000 parts per year to a high-volume production.

For both part geometries the fiber volume content, the part size and thickness are varied, and the impact on the costs is determined. In this regard the labeling “low” of the production scenario in Table 12 combines all parameters, which lead to low production costs.

Table 12: Varied part parameters

	Low	Medium	High	Unit
Part size	1.5	1	0.5	m²
Part thickness	3	2	1	mm
Fiber volume content	45	50	55	%

In Figure 22 the weight-specific production costs for curved parts for the three setups and production volumes are shown. The bars are divided into the different cost types, material costs (remaining in the part and cut-offs), machine costs for each process step and labor costs. In addition, the average utilization rate of the equipment is illustrated.

With an increased production volume (5,000 to 300,000 parts per year), a higher utilization rate can be achieved, resulting in lower manufacturing costs. A 20% cost reduction from around 80 to 63 €/kg is determined for the medium production setup for the base case in 2012. Also, the part-related fluctuations are decrease. Whereas for a small-scale production the part related boundary conditions have a significant influence on the weight-specific production costs (-17% decrease and 65% increase compared to the medium setup), the costs for a high-volume production only varies between 58 to 74 €/kg. However, the weight-specific cost fluctuations caused by the part size and thickness results mainly from the mass based allocation of the fixed costs. For the investigated process chain, the manufacturing times are almost independent from the part geometry. For example, it is assumed that the injection time changes with part size and thickness, but the total curing time remains the same. Furthermore, the average utilization rate of the required equipment in a small-scale production is very low. A slight increase of the production time will not result in an excessive workload, leading to higher investment costs due to the multiplication of equipment. In summary, the part manufacturing costs are almost similar. Consequently, larger and thicker parts lead to higher manufactured masses and therefore to lower weight-specific costs. However, with an increasing production volume, the machine costs and therefore the part size induced fluctuations decrease.

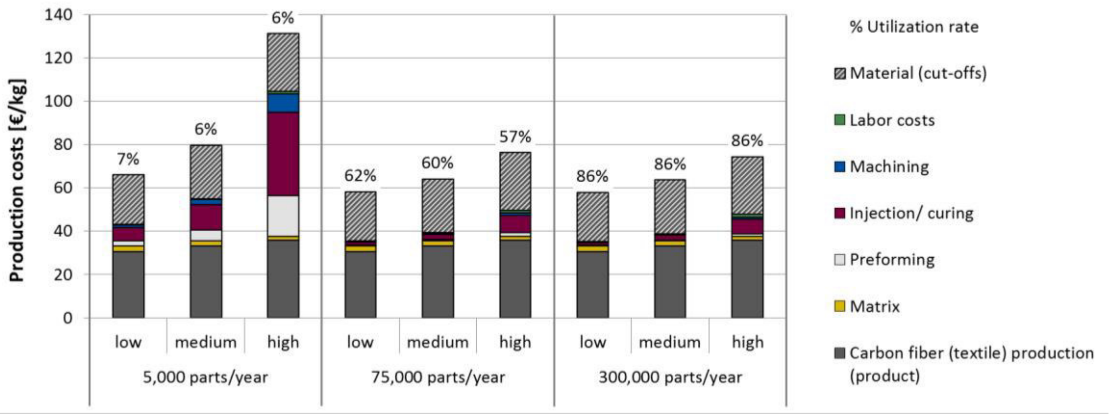


Figure 22: Impact of different production scenarios for curved part; base case in 2012

In Figure 23 the weight-specific production costs for profiles for the three setups and production volumes are shown. Again, a higher production quantity per year results in significant cost reductions. Also visible are the decreased part-related fluctuations due to the higher utilization rate of the equipment.

It is noticeable that the total production costs are significantly lower than for curved parts. Whereas as for a medium production setup the weight-specific costs of curved parts range from 80 to 64 €/kg, profile costs only vary between 35 and 22 €/kg depending on the production volume.
Furthermore, the material costs are less dominant. Explanations can be found in the different preforming techniques that require both specific raw materials and specific material amounts. Rovings are cheaper than NCF and can be used for near-net shape preforming techniques.

In detail, average material costs of 60 €/kg including cut-offs dominate the production costs of curved parts. For braided profiles, material costs of around 17 €/kg are considerably lower.

Comparing the machine costs, the preforming costs for a small-scale production of profiles are around 50% lower than for curved parts as the equipment for the forming step is not required. With a higher utilization rate, these cost savings become negligible. In contrast, the required multiplication of braiding machines for high-volume production leads to slightly higher preforming costs. Among the machine costs, the injection/curing process step is by far the main cost driver for both part geometries. For a medium setup, 4% (curved part) to 10% (profile) of the total production costs are related to this process step.

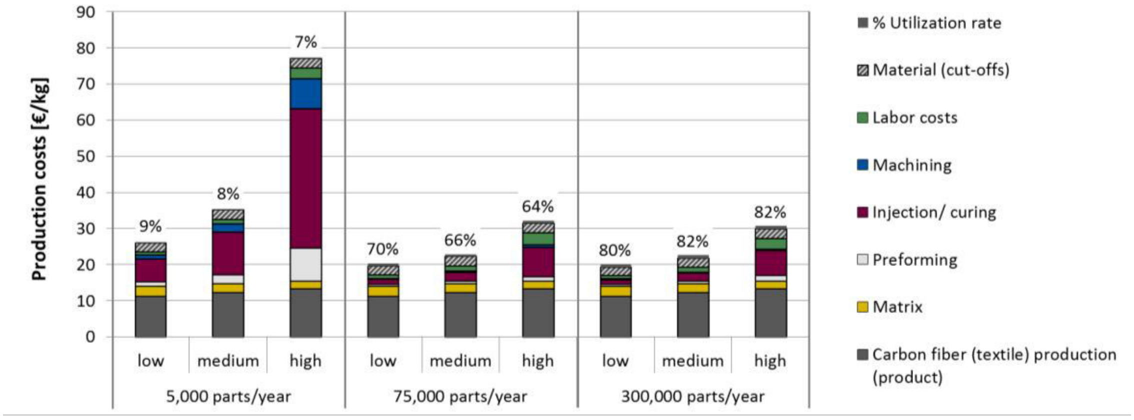


Figure 23: Impact of different production scenarios for profiles; base case in 2012

7.2 Analysis of different optimization measures

In analogy to the environmental assessment, the impact of different production and technology related measures on the production costs is investigated. However, all optimization possibilities related to the material production, e. g. the use of renewable energy or energy efficient processing, is summarized in one measure: the reduction of material prices. All varied measures are listed in Figure 27. The reduction potentials are evaluated for a medium production setup, considering the three defined annual production quantities. In addition, a sensitivity analysis is performed to identify further relevant parameters. Figure 25 and Figure 26 illustrate the cost reduction potential for curved parts and profiles, respectively. Each reduction potential is discussed and compared with each other.

Material price reduction for curved parts
Cutting the material prices in half has a significant impact on the production costs. Comparing the base case V1 with V2, a cost reduction between 35 and 55% can be achieved depending on the quantity per year. Material costs dominate the production costs in large-scale production, due to the high utilization rate of the equipment. Consequently, the highest reduction potential is given for high-volume; the costs decrease from 65 to 37 €/kg.

Impact of production related measures on the product costs

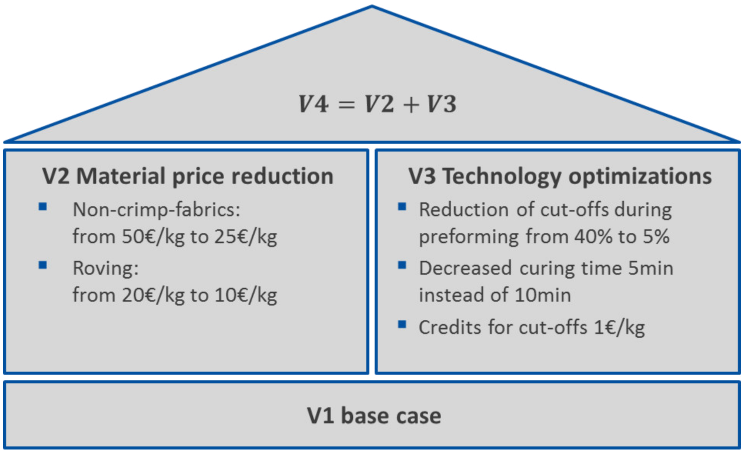


Figure 24: Overview of the investigated measures for a cost reduction

Reduction of cut-offs for curved parts

The application of a near net shape preforming technology is one optimization measure in V3. In this study, a 2D dry-fiber-placement system was investigated, enabling a direct placement of rovings. This results for two reasons in significant cost reductions. First, the material price is reduced from 50 €/kg for NCF to 20 €/kg (V3) and 10 kg/€ (V4) for rovings. Second, the cut-offs in preforming can be reduced from 40 to 5%. For curved parts, material costs of 60 €/kg for a NCF-RTM process chain are calculated. Using a near net shape preforming technology results in material costs of 17 €/kg in V3 and 10 €/kg in V4. In contrast, for small-scale production the machine costs increase from 20 to 28 €/kg. Reasons are higher equipment costs for a dry fiber placement system than for a 2D textile cutter. However, a near net shape preforming technology leads in total to cost reductions of 42% for a small-scale production and 62% for medium and high volumes.

Decreased curing time for curved parts

The development of highly reactive resin systems for the automotive industry leads to significant curing time reductions. In this study, an average decrease from 10 to 5 min was investigated, even though some resins already allow a sufficient cross-linking below 3 min. The shorter processing time leads to lower labor and variable equipment costs, e. g. energy and maintenance costs. In contrast a decrease of fixed costs (interests, rent and depreciation costs) can only be achieved at certain quantities. When the maximum equipment capacity is reached, the shortening of processing times prevents a multiplication of equipment and leads therefore to lower fixed costs. For the considered production volumes in this study, a cost reduction of 1% (small-scale) and 3% (large-scale) was calculated.

Credits for cut-offs for curved parts

In both preforming and machining, cut-offs occur, which can be recycled for new products. It is to be expected that cut-offs become a higher added value in near future. However, as the market potential is still difficult to assess, only a credit of 1 €/kg carbon fiber cut-offs is considered in this study. The calculated cost reduction potentials are lower than 1% compared to the base case.

Total cost reduction potential for curved parts

Some of the optimization measures interact. A simple linear addition of all reduction potentials is therefore not possible. For example, reduced cut-offs through the application of a near net shape preforming technology result in a lower impact of cut-off credits. The following reduction potentials compared to the base case V1 are calculated.

- 5,000 parts per year:
  V2: 36%; V3: 43%; V4: 52%
- 75,000 parts per year:
  V2: 44%; V3: 64%; V4: 75%
- 300,000 parts per year:
  V2: 44%; V3: 65%; V4: 76%

In summary, the total production costs can be reduced from around 80 €/kg (small-scale, V1) to below 18 €/kg (large-scale, V4) in best case.

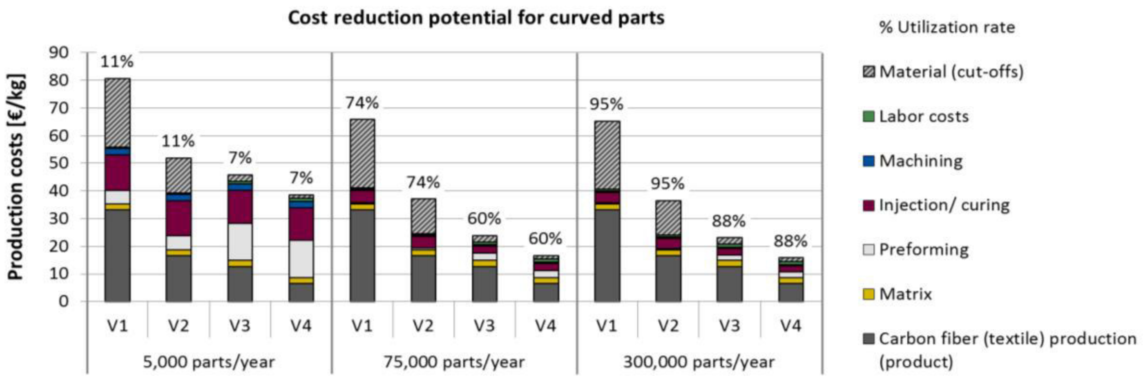


Figure 25: Cost reduction potential for curved parts

Material price reduction for profiles
Similar to curved parts, cutting the material price in half leads to significant cost reductions. However, the material costs of a braided profile are usually lower than for a curved part, due to lower cut-offs and direct processing of rovings. The total cost reduction potential is therefore smaller than for curved parts and ranges from 20 to 31%. Again, the largest cost savings can be achieved by a high-volume production (decrease from 24 to 16.5 €/kg).

Reduction of cut-offs for profiles
Cut-off rates of 5% are already assumed in the base case. Thus, no further reductions are investigated.

Decreased curing time for profiles
Due to the lower material expenses, the machine costs have a higher impact on the production costs. Shorting the processing time thus results in larger cost savings than for curved parts. For the considered production volumes, a cost reduction of 3.5% (small-scale) to 8.5% (large-scale) is calculated.

Credits for cut-offs for profiles
A credit of 1 € per kg carbon fiber cut-off results in cost reductions lower than 1% compared to the base case.

Cost reduction of all variations for profiles
In contrast to curved parts, the achievable reduction potentials are lower. Cheap raw materials and a preforming technology with lower cut-offs are already considered in the base case. The following reduction potentials compared to the base case were calculated.

- 5,000 parts per year:
  V2: 20%; V3: 3.5%; V4 23.5%
- 75,000 parts per year:
  V2: 30%; V3: 8.4%; V4 38.4%
- 300,000 parts per year:
  V2: 30.6%; V3: 8.5%; V4: 39.1%

In summary, the total production costs can be reduced from around 36 €/kg (small-scale, V1) below 15 €/kg (large-scale, V4) in best case.

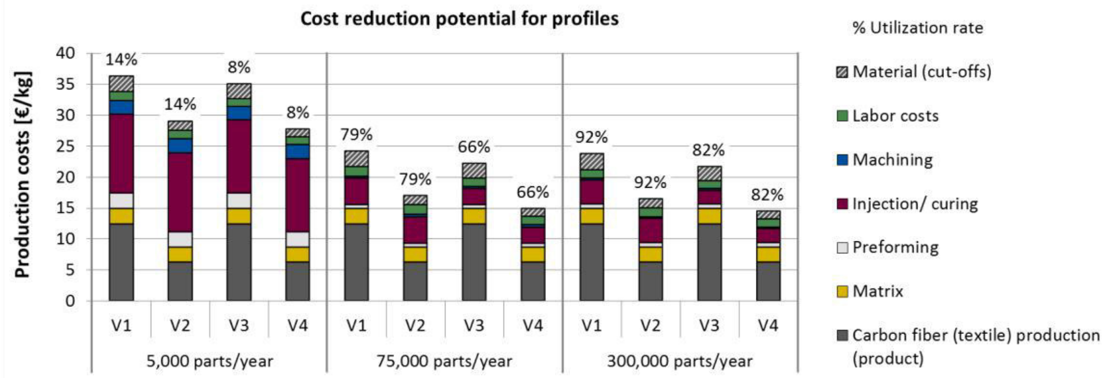


Figure 26: Cost reduction potential for profiles

Sensitivity analysis

In addition to the investigated optimization measures, further variables can have an influence on the production costs. Within a sensitivity analysis the impact on the costs is determined. On the one hand, non-influenceable parameters are investigated, e. g. interests, energy costs and rent. On the other hand, further material and technology based potentials are analyzed. For all optimization measures and considered production volumes the maximum fluctuations are calculated, illustrated in Figure 27.

Varying *interest* rates have an impact on the fixed machine costs. An increase from 3 to 8% can lead to increased costs of up to 16%. The current low-interest phase is therefore a huge advantage for capital-intensive manufacturing processes. However, the cost increase is marginal for large-scale productions at around 3%, due to the high utilization rates of the equipment. Increased *energy costs* in the part prodution have a comparatively low impact on the total production costs. This is also true for a *rent* and *wage* increase. The latter is due to the low share of labor cost on the total costs, caused by the highly automated processes. An *extra working shift* leads to higher labor costs due to shift surcharges. However, for production volumes with high utilization rates, machine costs decrease as less equipment is required. In total, a cost reduction potential of around 3% can be achieved. *Cost-effective resins* lead to cost decrease of around 1 €/kg in all production scenarios. The stacking of textiles is a fast and highly automated process, resulting in low manufacturing and labor costs. Near net shape placement technologies are, due to their complexity, limited regarding the achievable cycle times. To further reduce costs, a higher automation degree, continous processes and increased robustness are of importance. In this study, an increased layup rate from 25 to 50 kg/h is investigated. Especially for medium and high production volumes, a significant cost reduction of around 8% is calculated. Also, halving of braiding process times is possible, e. g. through the application of a double-ring braiding machine or automated change of the bobbins. An average reduction potential for high-volume production of 4.5% is calculated.

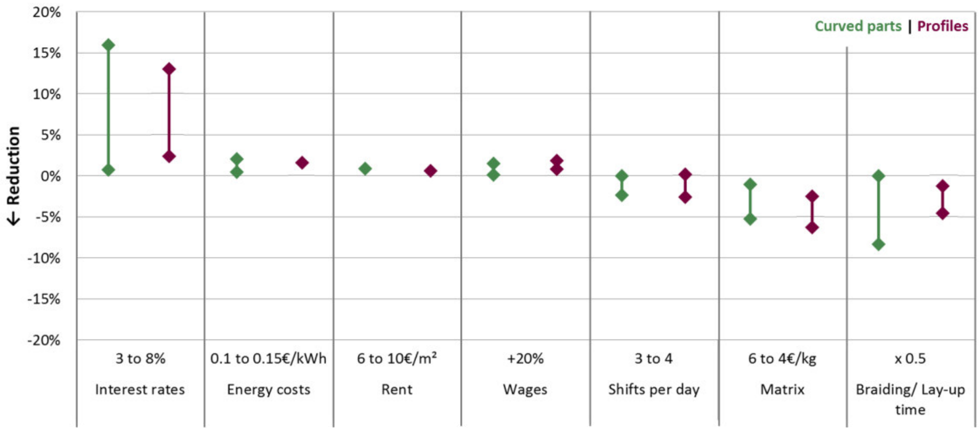


Figure 27: Sensitivity analysis of certain assumptions and further optimization measures

8 Summary

The German Leading-Edge Cluster MAI Carbon was launched in 2012 to become the leading global center for CFRP. 36 collaborative research projects were initiated with a total budget of almost 80 million €. The successful implementation of all the projects is the main requirement to reach the technological goals of MAI Carbon and to bring CFRP to a high-volume production. Cycle times below one minute, production costs of less than 18 € per kilogram CFRP part, and mostly automated process steps are just as important as a low environmental impact of CFRP. CFRP parts offer significant weight advantages over aluminum or GFRP. These weight advantages translate into energy savings during usage, if the material is mindfully integrated into e. g. an automotive or aerospace context. CFRP, if applied properly, offers the reduction of the environmental impact of anything that is moved by expending a lot of energy. This advantage has to be compared to the high environmental impact of the production of CFRP parts.

More than twelve individual CFRP production technologies have been examined and ten production process chains have been analyzed regarding their optimization potentials and their environmental impact. In best case 79 to 87% of the non-renewable primary energy demand can be saved. The use of renewable energy sources in the fiber and part production leads to a 38% reduction. 46% of the non-renewable primary energy demand can be saved by the implementation of technological measures and 28% through an optimized component design. Together, they allow dramatic reductions of the environmental impact of CFRP parts, thus revealing a path to a cleaner and correspondingly more successful future for CFRPs as the material of choice in mechanical, automotive and aerospace engineering. Furthermore, the investigations have shown that production parameters have a relevant impact on the process energy consumption and the environmental impact of the analyzed process chains. Component size, thickness, curing time and press type are the main levers.

The cost analysis for curved and profiled CFRP parts has shown that the production of smaller components leads to higher weight-specific costs especially for low volume production. Reasons can be found in the low utilization rate of the equipment and the process times, which are often not affected by the part size and thickness. Thus, the production of a thicker part results almost in the same machine costs, but more mass is produced compared to a smaller component. However, with an increasing production volume, the machine costs and therefore the part size induced fluctuations decrease. In addition, production costs can be reduced by up to 80% compared to 2012. Cutting the material prices in half, a cost reduction between 35 and 55% can be achieved depending on the quantity per year. A near net shape preforming technology leads to cost reductions of 42% for a small-scale production and 62% for medium and high volumes. In contrast to curved parts, the achievable cost reduction potentials are lower for the production of profiles. Cheap raw materials and a preforming technology with lower cut-offs are already considered in the base case. In best case cost reductions up to 60% compared to 2012 are possible. In conclusion, it was proven that the main cost target of MAI Carbon is realistic even today.

Now, six years after the launch of the leading-edge Cluster, it can be said, that the technological goals of 2020 have mostly been achieved already. It can be assumed that with further technological advancements in the area of cycle time savings, cost reduction, life cycle assessment, and much more, CFRP has a realistic chance to become one of the light weight material in the mass market. CFRP will not displace the established materials but will be used within an intelligent material mix. The success over the past five years is the key for job creation and the attraction of companies of SME and R&D institutions in the MAI region. As a strong network, the MAI region has established itself nationally and internationally and became a center for the CFRP industry.

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B List of abbreviations

ADP	abiotic resource depletion (“resource consumption”)
AFP	automated fiber placement
ATL	automated tape laying
BMBF	german federal ministry for education and research
CF	carbon fiber
CFRP	carbon fiber reinforced plastic
CNC	computer numerical control
CO_2	carbon dioxide
DFP	dry fiber placement
DP	duroplast (thermoset)
EP	epoxy resin
Eq	equivalents
EU-28	the 28 countries of the European Union
FRV	fuel reduction value
FVC	fiber volume content
GFRP	glass fiber reinforced plastics
GHG	greenhouse gas
GWP	global warming potential (“climate change”)
HT	high tenacity
IISI	international iron and steel institute
IR	infrared
LCA	life cycle assessment
LCI	life cycle inventory

lhv	lower heating value
MAI	Munich, Augsburg, Ingolstadt
NCF	non-crimp fabric
NEDC	new european driving cycle
No	number
nrr	non-renewable resources
OFAT	one factor at a time
PA6	polyamide 6 (Nylon 6)
PAN	polyacrylonitrile
PED	primary energy demand (“consumption of fossil energy resources”)
PTJ	project management jülich
R&D	research and development
RTM	resin transfer molding
SotA	state of the art
SME	small and medium-sized enterprise
Sz	Scenario (german: Szenario)
TFP	tailored fiber placement
TP	thermoplast
V	variant
w	with
WCM	wet compression molding
WLTC	worldwide harmonized light vehicles test cycle
w/o	without

C Appendix

C.1 Experimental setups

Nonwovens

Table 13: Nonwovens – machine specification

Specification of machine	
Machine type	Labscale wet laid nonwovens machine
Pulper parameters	
Filling capacity	Water: 35 l; Fiber: 450 g
Rotational frequency	50 to 2.500 rpm
Stock chest	
Filling capacity	1000 l
Supply rate	17 to 175 l/min
Layup parameters	
Production speed	1 to 10 m/min
Max. formation width	0.31 m
Drying	
No. of ventilator	2 before heater
Heater type	Hot air dryer
Usable space	1.4 m³

Table 14: Nonwovens – experimental setup

Experimental setup				
Pulper parameters				
Dispersion type	CMC			
Suspension composition	1 g CMC per 1 g carbon fiber; 0.5 g fibers per 1 liter water			
Rotational frequency	500 rpm to solve CMC in water; 2,000 rpm to disperse fibers in the CMC-water suspension			
Stock chest				
Rotational frequency	200 rpm			
Layup parameters				
Production speed	1 m/min			
Drying				
Power of ventilator	50%			
Heater temperature	180 °C			
Data acquisition				
Total energy demand	Energy consumption of pulper, heater and rest of machine (stock chest, layup, ventilator) are measured separately due to three separate electrical control cabinets			
Vaporized water	Weighing before and after the heater			
Variable parameters	**Trail 1**	**Trail 2**	**Trail 3**	**Trail 4**
Carbon fiber amount	900 g	900 g	368 g	368 g
PP fiber amount	---	---	432 g	432 g
Nominal CF/PP ratio	100/0 vol.%	100/0 vol.%	30/70 vol.%	30/70 vol.%
Nominal areal weight	150 g/m²	250 g/m²	150 g/m²	250 g/m²
Stock chest volume	1,800 l	1,800 l	1,600 l	1,600 l
Stock chest supply rate	90 l/min	150 l/min	90 l/min	150 l/min
Additional water supply	90 l/min	No	90 l/min	no
Produced nonwovens length	20 m	12 m	17.8 m	10.7 m
Real areal weight	134 g/m²	260 g/m²	122 g/m²	204 g/m²

Tailored-Fiber-Placement

Table 15: Tailored-Fiber-Placement – machine specification

Specification of machine	
Number of stitching heads	4
Stitching area per head	1 m²

Table 16: Tailored-Fiber-Placement – experimental setup

Experimental setup							
Pattern	Right-angle triangle (a = b = 1 m)						
Stitch type	Zigzag						
Stitch width	6 mm						
Stitch length	5 mm						
Variable parameters	**Trail 1**	**Trail 2**	**Trail 3**	**Trail 4**	**Trail 5**	**Trail 6**	**Trail 7**
No. of activated stitching heads	4	4	4	4	1	1	1
Rotation speed	1000 rpm	300 rpm	500 rpm	800 rpm	800 rpm	550 rpm	300 rpm

Dry-Fiber-Placement

Table 17: Dry-Fiber-Placement – machine specification

Specification of machine	
Layup system	Two different robot based (6-axis) w/wo an additional linear axis layup system
Robot type	KR150, KR180, KR210, KR240
Max. acceleration	1 m/s²
Max. speed	2 m/s
Layup width	ca. 200 mm and 50 mm
Positioning system	Vertical and horizontal
Creel	Electrical driven spools w/wo pressurized
Type of material	Roving's or binderyarns
Fixation	Apply of adhesive, heated up with an infrared system, activation of a binderyarn with an infrared or laser system

Table 18: Dry-Fiber-Placement – experimental setup

Experimental setup			
Data acquisition			
Total energy demand	Machine type 1: Separate electrical control cabinet for creel, robot, layup system (feeding unit and heating source) and adhesive heating system Machine type 2: Separate electrical control cabinet for robot, layup system (creel, feeding unit and heating source)		
Pressurized air consumption	Separate experimental setup, effort depending on the machine type		
Cooling water demand	Only required when a laser source is used for heating up the binder yarn; demand depends on laser power and is listed in the data sheet		
Machine type 1			
Creel haul-off speed	Idle speed (w/wo fan) and correlation of three haul-off speeds to power consumption		
Layup system haul-off speed	Idle speed and Correlation of three haul-off speeds to power consumption		
Infrared system	Correlation set power to real power consumption for three values depending on the heating time Correlation of edge angle to heating time		
Adhesive heating	Energy consumption for heating and holding the adhesive temperature		
Pressurized air consumption	Volume flow for each roving during layup		
Total energy demand	Flat plate (part complexity 1) and double curved part (part complexity 3)		
Machine type 2			
Creel haul-off speed	Correlation of six haul-off speeds and six motor rotation speeds to power consumption		
Layup system haul-off speed	Idle speed and material supply on/off		
Infrared heating system	Correlation of four different set power to power consumption averaged over different layup speeds/heating times (6m layup length with 0.3 m/s; 0.5 m/s and 1 m/s)		
Laser heating system	Correlation of seven different set power to power consumption averaged over different layup speeds/heating times; layup area 800 mm x 600 mm $[0 \vert 90 \vert +45 \vert -45]_{sym}$; Layer 1|2: 0.4 m/s, 500 W; layer 3|4: 0.4 m/s, 1000 W; layer 5|6: 0.4 m/s, 1500 W; layer 7|8: 0.4 m/s, 2000 W; Layer 1|2: 0.8 m/s, 2000 W; layer 3|4: 0.8 m/s, 2500 W; layer 5|6: 0.8 m/s, 3000 W; layer 7|8 0.8 m/s, 3500 W		
Pressurized air consumption	Correlation volume flow for four different pressure sets at each consumer (creel, head, lamp, roller)		
Total energy demand	Flat plate (part complexity 1) with two different layup speeds and double curved part (part complexity 3)		
Robot system			
Idle speed	KR150 | KR180 | KR210 | KR240		
Movement type	Max. movement of all 6 axis motors (PTP and linear)		
	KR210	KR180	
	PTP	PTP	linear
End effectors weight 0 kg	Set speed: 0 | 0.1 | 0.2 | 1 | 2 m/s	Set speed: 0 | 0.2 | 1.0 | 1.5 | 2.0 m/s	Set speed: 0 | 0.2 | 1.0 | 1.5 | 2.0 m/s
End effectors weight 80 kg	Set speed: 0 | 0.2 | 1.0 | 2.0 m/s	---	---
End effectors weight 140 kg	Set speed: 0 | 0.2 | 1.0 | 2.0 m/s	---	---

Braiding

Table 19: Braiding – machine specification

Specification of machine	
Size of machine	Ø 3 m
Type	Radial braiding machine
No. of filler yarns	32
No. of bobbins	64
Nominal rotating speed	up to 150 rpm
Exhaust system	on
Robot type	KR210 for braiding; KR180 for handling of complex part geometries

Table 20: Braiding –experimental setup

Experimental setup							
Data acquisition	Separate measurement of braiding machine, robot and exhaust system						
Exhaust system	Power consumption of process time						
Braiding machine	**Trail 1**	**Trail 2**	**Trail 3**	**Trail 4**	**Trail 5**	**Trail 6**	**Trail 7**
Rotation speed	Idle speed	150 rpm	112 rpm	75 rpm	50 rpm	150 rpm	150 rpm
Total moving weight (material and bobbin weight)	22 kg	22 kg	22 kg	22 kg	22 kg	11 kg	0 kg
Filler yarn	Braiding w/wo filler yarns						
Yarn tension	Three different yarn tensions						
Total energy demand (creel, robot, layup system,	Tube (part complexity 1) and curved tube with changes in cross-section (part complexity 3)						
Robot system							
Idle speed	KR150 | KR180 | KR210 | KR240						
Movement type	Max. movement of all 6 axis motors (PTP and linear)						
	KR210			KR180			
	PTP			PTP		linear	
End effectors weight 0 kg	Set speed: 0 | 0.1 | 0.2 | 1 | 2 m/s			Set speed: 0 | 0.2 | 1.0 | 1.5 | 2.0 m/s		Set speed: 0 | 0.2 | 1.0 | 1.5 | 2.0 m/s	
End effectors weight 80 kg	Set speed: 0 | 0.2 | 1.0 | 2.0 m/s			---		---	
End effectors weight 140 kg	Set speed: 0 | 0.2 | 1.0 | 2.0 m/s			---		---	

Appendix

Thermoplastic Fiber Placement

Table 21: Thermoplastic-Fiber-Placement – machine specification

Specification of machine	
Layup system	Two different robot based (6-axis) w/wo an additional linear axis layup system
Robot type	KR150, KR180, KR210, KR240
Max. acceleration	1 m/s^2
Max. speed	2 m/s
Layup width	ca. 200 mm and 50 mm
Positioning system	Vertical and horizontal
Creel	Electrical driven spools w/wo pressurized
Type of material	Slitted fiber reinforced thermoplastic tows
Fixation (no consolidation)	Apply of adhesive, heated up with an infrared system or activation of thermoplastic tows with a laser system

Table 22: Thermoplastic-Fiber-Placement –experimental setup

Experimental setup	
Data acquisition	
Total energy demand	Machine type 1: Separate electrical control cabinet for creel, robot, layup system (feeding unit and heating source) and adhesive heating system Machine type 2: Separate electrical control cabinet for robot, layup system (creel, feeding unit and heating source)
Pressurized air consumption	Only required for machine type 2
Cooling water demand	Only required for machine type 2; demand depends on laser power and is listed in the data sheet
Machine type 1	
Creel haul-off speed	Idle speed (w/wo fan) and correlation of three haul-off speeds to power consumption
Layup system haul-off speed	Idle speed and correlation of three haul-off speeds to power consumption
Infrared system	Correlation set power to real power consumption for three values depending on the heating time Correlation of edge angle to heating time
Adhesive heating	Energy consumption for heating and holding the adhesive temperature
Total energy demand (creel, robot, layup system,	Flat plate (part complexity 1) and double curved part (part complexity 3)
Machine type 2	
Creel haul-off speed	Correlation of six haul-off speeds and six motor rotation speeds to power consumption
Layup system haul-off speed	Idle speed and material supply on/off
Laser heating system	Correlation of seven different set power to power consumption averaged over different layup speeds/heating times; layup area 800 mm x 600 mm $[0\ \|90\ \|\ +45\ \|\ -45]_{sym}$; Layer 1|2: 0.4 m/s, 500 W; layer 3|4: 0.4 m/s, 1000 W; layer 5|6: 0.4 m/s, 1500 W; layer 7|8: 0.4 m/s, 2000 W; Layer 1|2: 0.8 m/s, 2000 W; layer 3|4: 0.8 m/s, 2500 W; layer 5|6: 0.8 m/s, 3000 W; layer 7|8 0.8 m/s, 3500 W
Pressurized air consumption	Correlation volume flow for four different pressure sets at each consumer (creel, head, lamp, roller)
Total energy demand (creel, robot, layup system,	Flat plate (part complexity 1) with two different layup speeds and double curved part (part complexity 3)
Robot system	
Idle speed	KR150 | KR180 | KR210 | KR240
Movement type	Max. movement of all 6 axis motors (PTP and linear)

	KR210	KR180	
	PTP	PTP	linear
End effectors weight 0 kg	Set speed: 0 | 0.1 | 0.2 | 1 | 2 m/s	Set speed: 0 | 0.2 | 1.0 | 1.5 | 2.0 m/s	Set speed: 0 | 0.2 | 1.0 | 1.5 | 2.0 m/s
End effectors weight 80 kg	Set speed: 0 | 0.2 | 1.0 | 2.0 m/s	---	---
End effectors weight 140 kg	Set speed: 0 | 0.2 | 1.0 | 2.0 m/s	---	---

Thermoplastic tape laying

Table 23: Thermoplastic tape laying – machine specification

Specification of machine	
Machine configuration	Gantry system
Placement area	2 m x 2 m
Tape width	50 mm to 150 mm
Welding system	Via ultrasonic
First ply fixation	Via suction fan
Number of suction fan zones	4 à 1 m²

Table 24: Thermoplastic tape laying – experimental setup

Experimental setup							
Data acquisition							
Total energy demand	One electrical control cabinet; separate measurement through on/off switch of respective consumers						
Pressurized air consumption	Measurement during layup/ sheet manufacturing						
Separate measurements							
Table rotation	Three different rotations speeds for a 360° rotation						
Linear movement of the table	Three different tape positions						
Ultrasonic welding device	Different no. of parallel welding spots						
Suction fan	Variable degree of coverage of the table (0% | 25%| 50%| 75% |100%) for different activated suction fan zones (1 to 4)						
Sheet manufacturing							
No. of layers and orientation	8; [0° | 90° | +45° | -45°]$_{\text{sym}}$						
	Trail 1	Trail 2	Trail 3	Trail 4	Trail 5	Trail 6	Trail 7
Part width	1.75 m	1.75 m	0.875 m	0.875 m	0.5 m	1.75 m	1.75 m
Part length	1.75 m	1.75 m	0.875 m	0.875 m	0.5 m	0.875 m	0.875 m
Tape width	150 mm	50 mm	150 mm	50 mm	75 mm	150 mm	50 mm

Appendix

Infrared heater

Table 25: Infrared heater – equipment specification

Specification of equipment	
Machine configuration	Medium wave radiation through special metal foils
Heater size	~0.5 m x 0.5 m
Heating power	~ 40 kW/m²

Table 26: Infrared heater – experimental setup

Experimental setup	
All 60 combinations of following parameters:	
Control (IR) temperature	100 °C | 125 °C | 150 °C | 175 °C | 200 °C
No. of layers	4 | 6 | 8 | 10 (areal weight 266 g/m²)
Distance between heater and preform	100 mm | 150 mm | 200 mm

Self-heated-toolings

Table 27: Self-heated toolings – Tool specification

Specification of tooling	
Tooling material	Steel
Heat transfer medium	Water
Others	Isolation between press and tooling
Tempering unit	
Heating power	8 kW to 30 kW for each tooling side
Cooling power	Around 55 kW
Volume flow cooling water	Around 15 l/min

Table 28: Self-heated toolings – experimental setup

Experimental setup			
	Tool 1	Tool 2	Tool 3
Part size	0.16 m²	0.6 m²	1.0 m²
Tooling mass	1,145 kg	6,000 kg	4,333 kg
Heating phase			
	RT --> 80 °C	RT --> 80 °C	---
	RT --> 100 °C	RT --> 100 °C	---
	RT --> 120 °C	RT --> 120 °C	---
Dwell phase			
	Min. 15 min @ 80 °C	Min. 15 min @ 80 °C	Min. 15 min @ 80 °C
	Min. 15 min @ 100 °C	Min. 15 min @ 100 °C	Min. 15 min @ 100 °C
	Min. 15 min @ 120 °C	Min. 15 min @ 120 °C	Min. 15 min @ 120 °C

Hydraulic press

Table 29: Hydraulic press – machine specification

Specification of machine							
	Press 1	Press 2	Press 3	Press 4	Press 5	Press 6	Press 7
Nominal closing force	650 kN	3,500 kN	6,000 kN	6,300 kN	10,000 kN	36,000 kN	38,000 kN
Use space	Unknown	Unknown	6 m²	1.8 m²	Unknown	6.1 m²	Unknown
Lifting speed	Unknown	Unknown	100 mm/s	800 mm/s	Unknown	1,200 mm/s	Unknown
Data type	Literature [32,33]	Literature [32,33]	Own measurements	Own measurements	Literature [32,34]	Own measurements	Literature [32,33]

Table 30: Hydraulic press – experimental setup

Experimental setup (Variation of pressure force and lifting speed in the closing, opening and dwell phase of the press)					
Press 1		Press 3		Press 6	
Press force	Lifting speed	Press force	Lifting speed	Press force	Lifting speed
0 kN	100 mm/s	500 kN	600 mm/s	500 kN	800 mm/s
300 kN	100 mm/s	1,000 kN	600 mm/s	1,000 kN	400 mm/s
1,000 kN	100 mm/s	2,000 kN	600 mm/s	1,000 kN	600 mm/s
2,000 kN	100 mm/s	3,000 kN	400 mm/s	1,000 kN	800 mm/s
3,000 kN	100 mm/s	3,000 kN	600 mm/s	1,000 kN	1,200 mm/s
		3,000 kN	800 mm/s	2,000 kN	800 mm/s
				3,000 kN	800 mm/s

Heating press

Table 31: Heating press – machine specification

Specification of machine		
	Press 1	Press 2
Nominal closing force	3,200 kN	1,400 kN
Use space	~ 1 m²	~ 0.5 m²
Lifting speed	up to 100 mm/s	up to 110 mm/s
Max. temperature	400 °C	360 °C
Type of heating	Electric	Heat transfer medium oil

Table 32: Heating press – experimental setup

Experimental setup			
Variation of pressure force and lifting speed in the closing, opening and dwell phase of the press			
Press 1		Press 2	
Press force	Lifting speed	Press force	Lifting speed
0 kN	5 mm/s	0 kN	110 mm/s
0 kN	25 mm/s	50 kN	110 mm/s
0 kN	50 mm/s	500 kN	110 mm/s
0 kN	75 mm/s	1,000 kN	110 mm/s
0 kN	100 mm/s	1,370 kN	110 mm/s
500 kN	100 mm/s		
1,000 kN	100 mm/s		
2,000 kN	100 mm/s		
3,200 kN	100 mm/s		
Variation of temperature			
Press 1		Press 2	
Heating phase		**Heating phase**	
RT --> 80 °C		RT --> 80 °C	
RT --> 120 °C		RT --> 120 °C	
RT --> 200 °C		RT --> 200 °C	
RT --> 280 °C		RT --> 280 °C	
		RT --> 360 °C	
Dwell phase		**Dwell phase**	
Min. 20 min @ 80 °C		Min. 20 min @ 80 °C	
Min. 20 min @ 120 °C		Min. 20 min @ 120 °C	
Min. 20 min @ 200 °C		Min. 20 min @ 200 °C	
Min. 20 min @ 280 °C		Min. 20 min @ 280 °C	
		Min. 20 min @ 360 °C	

Appendix

Pultrusion

Table 33: Pultrusion – machine specification

Specification of machine		
	Machine 1	Machine 2
Max. pulling force	10 t	Unknown
Max. haul-off speed	4 m/min	Unknown
Pulling unit	Alternating haul-off	Caterpillar haul-off
Tooling material	Steel	Steel
Tempering unit	Electric hotplates	Electric hotplates
Resin impregnation	Open bath and closed mold (dissolver and injection device is measured separately)	Open bath (dissolver is measured separately)

Table 34: Pultrusion – experimental setup

Experimental setup

Data acquisition	
Total energy demand	One electrical control cabinet; separate measurement through on/off switch of respective consumers
Pressurized air consumption	Measurement during production

Varing tooling mass and temperature					
	Tool 1	Tool 2	Tool 3	Tool 4	Tool 5
Tooling mass	~40 kg	~ 90 kg	~ 153 kg	~ 98 kg	~ 44 kg
Part profile section	2.7 cm²	3.7 cm²	3.6 cm²	1.7 cm²	1.1 cm²
Heating phase					
	RT --> 80 °C	RT --> 80 °C	RT --> 80 °C	RT --> 235 °C	RT --> 200 °C
	RT --> 120 °C	RT --> 120 °C	RT --> 120 °C		
	RT --> 160 °C	RT --> 160 °C	RT --> 160 °C		
	RT --> 200 °C	RT --> 200 °C	RT --> 200 °C		
	RT --> 220 °C	RT --> 220 °C	RT --> 220 °C		
Dwell phase					
	Min. 30 min @ 80 °C	Min. 30 min @ 80 °C	Min. 30 min @ 80 °C	Min. 30 min @ 220 °C	Min. 30 min @ 200 °C
	Min. 30 min @ 120 °C	Min. 30 min @ 120 °C	Min. 30 min @ 120 °C	Min. 30 min @ 235 °C	
	Min. 30 min @ 160 °C	Min. 30 min @ 160 °C	Min. 30 min @ 160 °C		
	Min. 30 min @ 200 °C	Min. 30 min @ 200 °C	Min. 30 min @ 200 °C		
	Min. 30 min @ 220 °C	Min. 30 min @ 220 °C	Min. 30 min @ 220 °C		

Varying haul-off speed	
Machine type 1	Machine type 2
0.3 | 0.4 | 0.5 | 0.7 | 0.8 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 m/min	0.6 | 0.7 | 0.8 | 0.82 | 0.86 m/min

Varying cross-section when sawing		
Cross-section 1	Cross-section 2	Cross-section 3
oval	Rectangular	Rectangular
0.63 cm²	3.6 cm²	9.2 cm²

Exhaust system (only on, when sawing)
Power consumption over process time

Auxiliary processes

Table 35: Auxiliary processes – specification of devices

Specification of equipment					
CNC-Cutter					
Type	Suitable for carbon fiber textiles				
Cutting area	1.3 m x 2.5 m				
Slitter					
Type	Powered upper and lower slitter				
Input material width	50 mm to 600 mm / 40 kg				
Input material thickness	0.1 mm to 0.5 mm				
Max. cutting speed	25 m/min				
Processable cutting width	6.35 mm to 150 mm				
Cutting tolerance	+/- 0.1 mm				
High pressure injection device					
Type of machine	Two-component injection device				
	Device 1	Device 2			
Max. amount of resin	~ 25 liter	~ 23 liter			
Max. amount of hardener	~ 14 liter	~ 23 liter			
Max. output rate	~ 8 liter/min	12 liter/min			
Max. operation pressure	290 bar	290 bar			
Rotary vane vacuum pump					
	Pump 1	Pump 2	Pump 3	Pump 4	Pump 5
Pumping speed	5 m³/h	10 m³/h	25 m³/h	250 m³/h	260 m³/h

Table 36: Auxiliary processes – experimental setups

Experimental setup				
CNC-Cutter				
Correlation three different coverage degree of the table with the process energy demand				
Slitter				
Varying slitting speed from 3 m/min to 20 m/min for tape and tow slitting				
High pressure injection device				
Correlation of three different resin temperatures (35 C | 60 °C | 80 °C) and injection pressures with the process energy demand				
Rotary vane vacuum pump (pressure difference (to atm)				
Pump 1	Pump 2	Pump 3	Pump 4	Pump 5
6 h @ 50 mbar	6 h @ 50 mbar			
6 h @ 400 mbar	6 h @ 400 mbar			
6 h @ 700 mbar	6 h @ 700 mbar			
6 h @ 940 mbar	6 h @ 940 mbar	10 min @ 940 mbar	2 h@ 940 mbar	2min @ 940 mbar

C.2 Boundary conditions for the evaluation of the environmental impact in chapter 5

NCF-RTM process chain

Table 37: NCF-RTM production parameters to evaluate the environmental impact in chapter 5

Constant parameters			
Fiber density	1.78 g/cm³	**Tool mounting time**	4 h
Resin type	Epoxy resin	**No. of working days per week**	5 days
Resin density	1.17 g/cm³	**No. of hours per shift**	8 h
Temperature of hardener before injection	35 °C	**Textile cut-offs (2D)**	20%
IR heater	Heating from both sides	**Preform cut-offs (3D)**	20%
Coverage degree 2D cutter	100%	**Rest of resin**	5%
Robot type for preform trimming (3D)	KR180 | KR210	**Cut-offs final machining**	10%
Weight end effector for preform trimming (3D)	< 70 kg	**Milling speed**	1.4 m/min
Demolding time	10 s		

Influencing parameters			
General parameters	**Low**	**Medium**	**High**
Fiber volume content (FVC) [%]	45	50	55
Textile areal weight [g/m²]	500	250	125
Part size [m²]	1.5	1	0.5
Part thickness [mm]	3	2	1
Utilization rate of press [%]	100	80	50
Preforming	**Low**	**Medium**	**High**
Textile tailoring (2D) cutting speed [m/min]	20	10	5
3D preforming			
IR heater temperature [°C]	150	200	250
IR heater size [m²]	4	6	8
Distance between heater and preform [mm]	80	100	150
Process time [s]	20	30	50
Process pressure [bar]	2.5	5	10
Preform trimming (3D) cutting speed [m/min]	20	10	5
HP-RTM	**Low**	**Medium**	**High**
Self-heated tooling			
Tooling mass to part size [kg/m²]	4333	7153	10000
Tooling temperature [°C]	80	120	140
Injection- and curing time [min]	3	5	10
Process pressure [bar]	60	80	100
Tool changes per week	1	1	5
No. of shifts per day	3	2	1
Tool heating	daily	daily	Once a week
Vacuum pump pumping speed [m³/h]	10	120	260
High pressure injection device			
Resin temperature before injection [°C]	35	60	80
Resin output rate [kg/min]	4	2	1

Nonwovens-RTM process chain

Table 38: Nonwovens-RTM production parameters to evaluate the environmental impact in chapter 5

Constant parameters			
Fiber density	1.78 g/cm³	**Weight end effector for preform trimming**	< 70 kg
Resin type	Epoxy resin	**Demolding time**	10 s
Resin density	1.17 g/cm³	**Tool mounting time**	4 h
Temperature of hardener before injection	35 °C	**No. of working days per week**	5 days
Nonwovens formation width	0.31 m	**No. of hours per shift**	8 h
Amount of fibers in the pulper	0.45 kg	**Textile cut-offs (2D)**	20%
Time for dispersion	0.3 h	**Preform cut-offs (3D)**	20%
Preparation time for nonwoven machine	0.8 h per day	**Rest of resin**	5%
IR heater	Heating from both sides	**Cut-offs final machining**	10%
Coverage degree 2D cutter	100%	**Milling speed**	1.4 m/min
Robot type for preform trimming (3D)	KR180 | KR210		

Influencing parameters			
General parameters	**Low**	**Medium**	**High**
Fiber volume content (FVC) [%]	45	50	55
Textile areal weight [g/m²]	250	200	150
Part size [m²]	1.5	1	0.5
Part thickness [mm]	3	2	1
Utilization rate of press [%]	100	80	50
Preforming	**Low**	**Medium**	**High**
Nonwovens production			
Production speed [m/min]	10	5	1
Rotational frequency pulper [prm]	500	2000	2000
Textile tailoring (2D) cutting speed [m/min]	20	10	5
3D preforming			
IR heater temperature [°C]	150	200	250
IR heater size [m²]	4	6	8
Distance between heater and preform [mm]	80	100	150
Process time [s]	20	30	50
Process pressure [bar]	2.5	5	10
Preform trimming (3D) cutting speed [m/min]	20	10	5
HP-RTM	**Low**	**Medium**	**High**
Self-heated tooling			
Tooling mass to part size [kg/m²]	4333	7153	10000
Tooling temperature [°C]	80	120	140
Injection- and curing time [min]	3	5	10
Process pressure [bar]	60	80	100
Tool changes per week	1	1	5
No. of shifts per day	3	2	1
Tool heating	daily	daily	Once a week
Vacuum pump pumping speed [m³/h]	10	120	260
High pressure injection device			
Resin temperature before injection [°C]	35	60	80
Resin output rate [kg/min]	4	2	1

Appendix

TFP-RTM process chain

Table 39: TFP-RTM production parameters to evaluate the environmental impact in chapter 5

Constant parameters			
Fiber density	1.78 g/cm³	**Demolding time**	10 s
Resin type	Epoxy resin	**Tool mounting time**	4 h
Resin density	1.17 g/cm³	**No. of working days per week**	5 days
Temperature of hardener before injection	35 °C	**No. of hours per shift**	8 h
Stitch pattern	Zigzag	**Textile cut-offs (2D)**	0%
Basic material	NCF	**Preform cut-offs (3D)**	5%
IR heater	Heating from both sides	**Rest of resin**	5%
Robot type for preform trimming (3D)	KR180 | KR210	**Cut-offs final machining**	10%
Weight end effector for preform trimming	< 70 kg	**Milling speed**	1.4 m/min

Influencing parameters			
General parameters	**Low**	**Medium**	**High**
Fiber volume content (FVC) [%]	45	50	55
Part size [m²]	1.5	1	0.5
Part thickness [mm]	3	2	1
Utilization rate of press [%]	100	80	50
Preforming	**Low**	**Medium**	**High**
Basic material			
Areal weight [g/m²]	250	200	150
Fiber type	Glas	Carbon	Carbon
Tailored-Fiber-Placement			
No. of parallel stitching heads	4	4	1
Rotation speed [rpm]	1000	500	300
Roving type	50k	24k	12k
3D preforming			
IR heater temperature [°C]	150	200	250
IR heater size [m²]	4	6	8
Distance between heater and preform [mm]	80	100	150
Process time [s]	20	30	50
Process pressure [bar]	2.5	5	10
Preform trimming (3D) cutting speed [m/min]	20	10	5
HP-RTM	**Low**	**Medium**	**High**
Self-heated tooling			
Tooling mass to part size [kg/m²]	4333	7153	10000
Tooling temperature [°C]	80	120	140
Injection- and curing time [min]	3	5	10
Process pressure [bar]	60	80	100
Tool changes per week	1	1	5
No. of shifts per day	3	2	1
Tool heating	daily	daily	Once a week
Vacuum pump pumping speed [m³/h]	10	120	260
High pressure injection device			
Resin temperature before injection [°C]	35	60	80
Resin output rate [kg/min]	4	2	1

DFP-RTM process chain

Table 40: DFP-RTM production parameters to evaluate the environmental impact in chapter 5

Constant parameters

Fiber density	1.78 g/cm³	Weight end effector for preform trimming	< 70 kg
Resin type	Epoxy resin	**Demolding time**	10 s
Resin density	1.17 g/cm³	**Tool mounting time**	4 h
Temperature of hardener before injection	35 °C	**No. of working days per week**	5 days
Share of "on surface" time on layup time	70%	**No. of hours per shift**	8 h
Share of "off surface" time on layup time	30%	**Textile cut-offs (2D)**	0%
Set cooling pressure placement roller	2 bar	**Preform cut-offs (3D)**	5%
Set pressure IR lamp	3 bar	**Rest of resin**	5%
Set pressure creel	1 bar	**Cut-offs final machining**	10%
IR heater	Heating from both sides	**Milling speed**	1.4 m/min
Robot type for preform trimming (3D)	KR180 | KR210		

Influencing parameters

General parameters	**Low**	**Medium**	**High**
Fiber volume content (FVC) [%]	45	50	55
Areal weight [g/m²]	250	200	150
Part size [m²]	1.5	1	0.5
Part thickness [mm]	3	2	1
Utilization rate of press [%]	100	80	50
Preforming	**Low**	**Medium**	**High**
Dry-Fiber-Placement			
Layup rate [kg/h]	50	25	10
Head layup width [mm]	300	200	100
Roving type	50k	24k	12k
Layup system	Machine type 2 IR	Machine type 1	Machine type 2 laser
Layup orientation	0°	30°	60°
3D preforming			
IR heater temperature [°C]	150	200	250
IR heater size [m²]	4	6	8
Distance between heater and preform [mm]	80	100	150
Process time [s]	20	30	50
Process pressure [bar]	2.5	5	10
Preform trimming (3D) cutting speed [m/min]	20	10	5
HP-RTM	**Low**	**Medium**	**High**
Self-heated tooling			
Tooling mass to part size [kg/m²]	4333	7153	10000
Tooling temperature [°C]	80	120	140
Injection- and curing time [min]	3	5	10
Process pressure [bar]	60	80	100
Tool changes per week	1	1	5
No. of shifts per day	3	2	1
Tool heating	daily	daily	Once a week
Vacuum pump pumping speed [m³/h]	10	120	260
High pressure injection device			
Resin temperature before injection [°C]	35	60	80
Resin output rate [kg/min]	4	2	1

Appendix

Braiding-RTM process chain

Table 41: Braiding-RTM production parameters to evaluate the environmental impact in chapter 5

Constant parameters			
Fiber density	1.78 g/cm³	**Demolding time**	10 s
Resin type	Epoxy resin	**Tool mounting time**	4 h
Resin density	1.17 g/cm³	**No. of working days per week**	5 days
Temperature of hardener before injection	35 °C	**No. of hours per shift**	8 h
Braiding rotation speed	150 rpm	**Textile cut-offs (2D)**	0%
No. of filler yarns	32	**Preform cut-offs (3D)**	5%
No. of bobbins	64	**Rest of resin**	5%
Robot type for preform trimming (3D)	KR180 | KR210	**Cut-offs final machining**	10%
Weight end effector for preform trimming	< 70 kg	**Milling speed**	1.4 m/min

Influencing parameters

General parameters	**Low**	**Medium**	**High**
Fiber volume content (FVC) [%]	45	50	55
Part size [m²]	1.5 (ø 150 mm)	1 (ø 92.5 mm)	0.5 (ø 35 mm)
Part thickness [mm]	3	2	1
Utilization rate of press [%]	100	80	50
Preforming	**Low**	**Medium**	**High**
Braiding			
Filler yarns	Yes	Yes	no
Roving type	50k	24k	12k
No. of robots for braiding and handling	1	2	3
Preform trimming (3D) cutting speed [m/min]	20	10	5
HP-RTM	**Low**	**Medium**	**High**
Self-heated tooling			
Tooling mass to part size [kg/m²]	4333	7153	10000
Tooling temperature [°C]	80	120	140
Injection- and curing time [min]	3	5	10
Process pressure [bar]	60	80	100
Tool changes per week	1	1	5
No. of shifts per day	3	2	1
Tool heating	daily	daily	Once a week
Vacuum pump pumping speed [m³/h]	10	120	260
High pressure injection device			
Resin temperature before injection [°C]	35	60	80
Resin output rate [kg/min]	4	2	1

Pultrusion

Table 42: Pultrusion production parameters to evaluate the environmental impact in chapter 5

Constant parameters			
Fiber density	1.78 g/cm³	**No. of working days per week**	5 days
Resin type	Epoxy | PU resin	**No. of hours per shift**	8 h
Resin density	1.17 | 1.16 g/cm³	**Textile cut-offs (2D)**	0%
Temperature of hardener before injection	35 °C	**Preform cut-offs (3D)**	0%
Demolding time	10 s	**Cut-offs final machining**	10%
Tool mounting time	4 h	**Milling speed**	1.4 m/min

Influencing parameters

General parameters	**Low**	**Medium**	**High**
Resin system	PU	Epoxy	Epoxy
Machine type	Type 1	Type 1	Type 2
Fiber volume content (FVC) [%]	55	60	65
Tooling mass [kg]	135	153	44
Cross section [cm²]	5.2	3.6	1.1
Profile length [m]	1.5	1	0.5
Tooling temperature [°C]	150	180	210
Haul-off speed [m/min]	2	0.6	0.15
Impregnation	Closed mold	Open bath	Open bath
Rest of resin	5%	7.5%	7.5%
Operation time saw	Only if required	Only if required	Switched on permanently
No. of shifts per day	3	2	1
Tool heating	daily	daily	Once a week

Appendix

Fabric-organosheet-TP-forming process chain

Table 43: Fabric-organosheet-TP-forming production parameters to evaluate the environmental impact in chapter 5

Constant parameters			
Fiber density	1.78 g/cm³	**Tool mounting time**	4 h
Matrix system	PP | PA6	**No. of working days per week**	5 days
Matrix density	0.9075 | 1.14 g/cm³	**No. of hours per shift**	8 h
Lifting speed of press	110 mm/s	**Organosheet cut-offs (2D)**	40%
IR heater	Heating from both sides	**Rest of matrix**	0%
Demolding time	10 s	**Cut-offs final machining**	10%
		Milling speed	1.4 m/min

Influencing parameters			
General parameters	**Low**	**Medium**	**High**
Fiber volume content (FVC) [%]	45	50	55
Matrix type	PP	PA6	PA6
Part size [m²]	1.5	1	0.5
Part thickness [mm]	3	2	1
Utilization rate of press [%]	100	80	50
Organosheet production	**Low**	**Medium**	**High**
Fabric areal weight [g/m²]	500	250	125
Press type	Electric heated	Electric heated	Oil heated
Press temperature zone 1 [°C]	PP: 205 | PA6: 260	PA6: 280	PA6: 300
Press temperature zone 2 [°C]	PP: 50 | PA6: 60	PA6: 80	PA6: 100
Process pressure zone 1 [bar]	PP: 40 | PA6: 1	PA6: 1	PA6: 1
Process pressure zone 2 [bar]	PP: 40 | PA6: 20	PA6: 40	PA6: 60
Process time zone 1 [min]	PP: 10 | PA6 5	PA6: 10	PA6: 15
Process time zone 2 [min]	PP: 4 | PA6: 5	PA6: 10	PA6: 15
Thermoplastic forming	**Low**	**Medium**	**High**
IR heater			
Process time [min]	1	1.5	2
IR heater size [m²]	4	6	8
IR heater material	Quartz	Metal	ceramic
Self-heated tooling			
Tooling mass to part size [kg/m²]	4333	7153	10000
Tooling temperature [°C]	PP: 50 | PA6: 60	PA6: 80	PA6: 100
Process time [min]	1	1.5	2
Process pressure [bar]	5	8	15
Tool changes per week	1	1	5
No. of shifts per day	3	2	1
Tool heating	daily	daily	Once a week

TP-nonwovens-organosheet-TP-forming process chain

Table 44: TP-nonwovens-organosheet-TP-forming production parameters to evaluate the environmental impact in chapter 5

Constant parameters			
Fiber density	1.78 g/cm³	**IR heater**	Heating from both sides
Matrix system	PP | PA6	**Demolding time**	10 s
Matrix density	0.9075 | 1.14 g/cm³	**Tool mounting time**	4 h
Nonwovens formation width	0.31 m	**No. of working days per week**	5 days
Amount of fibers in the pulper	0.45 kg	**No. of hours per shift**	8 h
Time for dispersion	0.3 h	**Organosheet cut-offs (2D)**	40%
Preparation time for nonwoven machine	0.8 h per day	**Rest of matrix**	0%
Lifting speed of press	110 mm/s	**Cut-offs final machining**	10%
		Milling speed	1.4 m/min

Influencing parameters			
General parameters	**Low**	**Medium**	**High**
Fiber volume content (FVC) [%]	45	50	55
Matrix type	PP	PA6	PA6
Part size [m²]	1.5	1	0.5
Part thickness [mm]	3	2	1
Utilization rate of press [%]	100	80	50
Organosheet production	**Low**	**Medium**	**High**
Nonwovens production			
Areal weight [g/m²]	250	200	150
Production speed [m/min]	10	5	1
Rotational frequency pulper [prm]	500	2000	2000
Organosheet manufacturing			
Press type	Electric heated	Electric heated	Oil heated
Press temperature zone 1 [°C]	PP: 205 | PA6: 260	PA6: 280	PA6: 300
Press temperature zone 2 [°C]	PP: 50 | PA6: 60	PA6: 80	PA6: 100
Process pressure zone 1 [bar]	PP: 40 | PA6: 1	PA6: 1	PA6: 1
Process pressure zone 2 [bar]	PP: 40 | PA6: 20	PA6: 40	PA6: 60
Process time zone 1 [min]	PP: 10 | PA6 5	PA6: 10	PA6: 15
Process time zone 2 [min]	PP: 4 | PA6: 5	PA6: 10	PA6: 15
Thermoplastic forming	**Low**	**Medium**	**High**
IR heater			
Process time [min]	1	1.5	2
IR heater size [m²]	4	6	8
IR heater material	Quartz	Metal	ceramic
Self-heated tooling			
Tooling mass to part size [kg/m²]	4333	7153	10000
Tooling temperature [°C]	PP: 50 | PA6: 60	PA6: 80	PA6: 100
Process time [min]	1	1.5	2
Process pressure [bar]	5	8	15
Tool changes per week	1	1	5
No. of shifts per day	3	2	1
Tool heating	daily	daily	Once a week

Appendix

TP-AFP-consolidation-TP-forming process chain

Table 45: TP-AFP-consolidation-TP-forming production parameters to evaluate the environmental impact in chapter 5

Constant parameters			
Fiber density	1.78 g/cm³	**IR heater**	Heating from both sides
Matrix system	PP | PA6	**Demolding time**	10 s
Matrix density	0.9075 | 1.14 g/cm³	**Tool mounting time**	4 h
Share of "on surface" time on layup time	70%	**No. of working days per week**	5 days
Share of "off surface" time on layup time	30%	**No. of hours per shift**	8 h
Set cooling pressure placement roller	5 bar	**Organosheet cut-offs (2D)**	5%
Set pressure creel	1 bar	**Rest of matrix**	0%
Lifting speed of press	110 mm/s	**Cut-offs final machining**	10%
		Milling speed	1.4 m/min
Influencing parameters			
General parameters	**Low**	**Medium**	**High**
Fiber volume content (FVC) [%]	45	50	55
Matrix type	PP	PA6	PA6
Part size [m²]	1.5	1	0.5
Part thickness [mm]	3	2	1
Utilization rate of press [%]	100	80	50
Organosheet production	**Low**	**Medium**	**High**
Tape production			
Areal weight [g/m²]	250	200	150
Press type	Electric heated	Electric heated	Oil heated
Press temperature zone 1 [°C]	PP: 205 | PA6: 260	PA6: 280	PA6: 300
Press temperature zone 2 [°C]	PP: 50 | PA6: 60	PA6: 80	PA6: 100
Process pressure zone 1 | 2 [bar]	1 | 10	1 | 10	1 | 10
Process time zone 1 and zone 2 [s]	PP: 15 | PA6 20	PA6: 20	PA6: 20
Slitter			
Cutting speed [m/min]	20	17	10
Original role width [mm]	450	300	150
Thermoplastic fiber placement			
Layup rate [kg/h]	50	25	10
Head layup width [mm]	300	200	100
Fixation system	Adhesive	Adhesive	Laser
Layup system	Machine type 1	Average	Machine type 2 laser
Consolidation			
Press type	Electric heated	Electric heated	Oil heated
Press temperature zone 1 [°C]	PP: 205 | PA6: 260	PA6: 280	PA6: 300
Press temperature zone 2 [°C]	PP: 50 | PA6: 60	PA6: 80	PA6: 100
Process pressure zone 1 [bar]	PP: 40 | PA6: 1	PA6: 1	PA6: 1
Process pressure zone 2 [bar]	PP: 40 | PA6: 20	PA6: 40	PA6: 60
Process time zone 1 and 2 [min]	1	1.5	2
Thermoplastic forming	**Low**	**Medium**	**High**
IR heater			
Process time [min]	1	1.5	2
IR heater size [m²]	4	6	8
IR heater material	Quartz	Metal	ceramic
Self-heated tooling			
Tooling mass to part size [kg/m²]	4333	7153	10000
Tooling temperature [°C]	PP: 50 | PA6: 60	PA6: 80	PA6: 100
Process time [min]	1	1.5	2
Process pressure [bar]	5	8	15
Tool changes per week	1	1	5
No. of shifts per day	3	2	1
Tool heating	daily	daily	Once a week

TP-ATL consolidation-TP-forming process chain

Table 46: TP-ATL-consolidation-TP-forming production parameters to evaluate the environmental impact in chapter 5

Constant parameters

Fiber density	1.78 g/cm^3	**No. of working days per week**	5 days
Matrix system	PP | PA6	**No. of hours per shift**	8 h
Matrix density	0.9075 | 1.14 g/cm^3	**Organosheet cut-offs (2D)**	5%
Lifting speed of press	110 mm/s	**Rest of matrix**	0%
IR heater	Heating from both sides	**Cut-offs final machining**	10%
Demolding time	10 s	**Milling speed**	1.4 m/min
Tool mounting time	4 h		

Influencing parameters

General parameters	**Low**	**Medium**	**High**
Fiber volume content (FVC) [%]	45	50	55
Matrix type	PP	PA6	PA6
Part size [m^2]	1.5	1	0.5
Part thickness [mm]	3	2	1
Utilization rate of press [%]	100	80	50
Organosheet production	**Low**	**Medium**	**High**
Tape production			
Areal weight [g/m^2]	250	200	150
Press type	Electric heated	Electric heated	Oil heated
Press temperature zone 1 [°C]	PP: 205 | PA6: 260	PA6: 280	PA6: 300
Press temperature zone 2 [°C]	PP: 50 | PA6: 60	PA6: 80	PA6: 100
Process pressure zone 1 | 2 [bar]	1 | 10	1 | 10	1 | 10
Process time zone 1 and zone 2 [s]	PP: 15 | PA6 20	PA6: 20	PA6: 20
Slitter			
Cutting speed [m/min]	20	17	10
Original role width [mm]	450	300	150
Thermoplastic tape laying			
Tape width [mm]	150	100	50
Layup orientation	0°	Quasi-isotropic	+/-45°
Consolidation			
Press type	Electric heated	Electric heated	Oil heated
Press temperature zone 1 [°C]	PP: 205 | PA6: 260	PA6: 280	PA6: 300
Press temperature zone 2 [°C]	PP: 50 | PA6: 60	PA6: 80	PA6: 100
Process pressure zone 1 [bar]	PP: 40 | PA6: 1	PA6: 1	PA6: 1
Process pressure zone 2 [bar]	PP: 40 | PA6: 20	PA6: 40	PA6: 60
Process time zone 1 and 2 [min]	1	1.5	2
Thermoplastic forming	**Low**	**Medium**	**High**
IR heater			
Process time [min]	1	1.5	2
IR heater size [m^2]	4	6	8
IR heater material	Quartz	Metal	ceramic
Self-heated tooling			
Tooling mass to part size [kg/m^2]	4333	7153	10000
Tooling temperature [°C]	PP: 50 | PA6: 60	PA6: 80	PA6: 100
Process time [min]	1	1.5	2
Process pressure [bar]	5	8	15
Tool changes per week	1	1	5
No. of shifts per day	3	2	1
Tool heating	daily	daily	Once a week

C.3 Boundary conditions for the evaluation of the environmental impact in chapter 6

NCF-RTM process chain – part-related parameters

Table 47: NCF-RTM production parameters to evaluate the environmental impact in chapter 6.2

Constant parameters			
General parameters			
Fiber density	1.78 g/cm³	No. of hours per shift	8 h
Resin type	Epoxy resin	Textile cut-offs (2D)	20%
Resin density	1.17 g/cm³	Preform cut-offs (3D)	20%
Utilization rate of press	80%	Rest of resin	5%
Demolding time	10 s	Cut-offs final machining	10%
Tool mounting time	4 h	Milling speed	1.4 m/min
No. of working days per week	5 days		
Preforming			
Stack manufacturing		3D preforming	
Textile areal weight	250 g/m²	IR heater temperature	200 °C
Coverage degree 2D cutter	100%	IR heater size	6 m²
Cutting speed	10 m/min	Distance between heater/preform	100 mm
Preform trimming (3D)		IR heater	Heating from both sides
Robot type	KR180 | KR210	Process time	30 s
Weight end effector	< 70 kg	Process pressure	5 bar
Cutting speed	10 m/min		
HP-RTM			
Self-heated tooling		High pressure injection device	
Tooling mass to part size	7153 kg/m²	Resin temperature before injection	60 °C
Tooling temperature	120 °C	Temperature of hardener before injection	35 °C
Injection- and curing time	5 min	Resin output rate	2 kg/min
Process pressure	80 bar	Vacuum pump pumping speed	120 m³/h
Tool changes per week	1		
No. of shifts per day	2		
Tool heating	Daily		
Varied parameters	**Large, thick part; FVC 45%**	**Medium**	**Small, thin part; FVC 55%**
Fiber volume content (FVC) [%]	45	50	55
Part size [m²]	1.5	1	0.5
Part thickness [mm]	3	2	1

Braiding-RTM process chain – part-related parameters

Table 48: Braiding-RTM production parameters to evaluate the environmental impact in chapter 6.2

Constant parameters			
General parameters			
Fiber density	1.78 g/cm³	No. of hours per shift	8 h
Resin type	Epoxy resin	Textile cut-offs (2D)	0%
Resin density	1.17 g/cm³	Preform cut-offs (3D)	5%
Utilization rate of press	80%	Rest of resin	5%
Demolding time	10 s	Cut-offs final machining	10%
Tool mounting time	4 h	Milling speed	1.4 m/min
No. of working days per week	5 days		
Preforming			
Braiding		Preform trimming (3D)	
Rotation speed	150 rpm	Robot type	KR180 | KR210
No. of filler yarns	32	Weight end effector	< 70 kg
No. of bobbins	64	Cutting speed	10 m/min
Robot type	KR180 | KR210		
Weight end effector	< 70 kg		
Filler yarns	Yes		
Roving type	24k		
No. of robots for braiding/handling	2		
HP-RTM			
Self-heated tooling		High pressure injection device	
Tooling mass to part size	7153 kg/m²	Resin temperature before injection	60 °C
Tooling temperature	120 °C	Temperature of hardener before injection	35 °C
Injection- and curing time	5 min	Resin output rate	2 kg/min
Process pressure	80 bar	Vacuum pump pumping speed	120 m³/h
Tool changes per week	1		
No. of shifts per day	2		
Tool heating	Daily		
Varied parameters	**Large, thick profile; FVC 45%**	**Medium**	**Small, thin profile; FVC 55%**
Fiber volume content (FVC) [%]	45	50	55
Part size [m²]	1.5 (ø 150 mm)	1 (ø 92.5 mm)	0.5 (ø 35 mm)
Part thickness [mm]	3	2	1

Appendix

Fabric-organosheet-TP-forming process chain

Table 49: Fabric-organosheet-TP-forming production parameters to evaluate the environmental impact in chapter 6.2

Constant parameters			
General parameters			
Fiber density	1.78 g/cm³	Tool mounting time	4 h
Matrix system	PA6	No. of working days per week	5 days
Matrix density	1.14 g/cm³	No. of hours per shift	8 h
Lifting speed of press	110 mm/s	Organosheet cut-offs (2D)	40%
Demolding time	10 s	Rest of matrix	0%
Utilization rate of press	80%	Cut-offs final machining	10%
		Milling speed	1.4 m/min
Organosheet production			
Fabric areal weight	250 g/m²	Process pressure zone 1	1 bar
Press type	Electric heated	Process pressure zone 2	40 bar
Press temperature zone 1	280 °C	Process time zone 1	10 min
Press temperature zone 2	80 °C	Process time zone 2	10 min
Thermoplastic forming			
IR heater		Self-heated tooling	
Process time	1.5 min	Tooling mass to part size	7153 kg/m²
IR heater size	6 m²	Tooling temperature	80 °C
IR heater material	Metal	Process time	1.5 min
IR heater	Heating from both sides	Process pressure	8 bar
		Tool changes per week	1
		No. of shifts per day	2
		Tool heating	daily
Varied parameters	**Large, thick part; FVC 45%**	**Medium**	**Small, thin part; FVC 55%**
Fiber volume content (FVC) [%]	45	50	55
Part size [m²]	1.5	1	0.5
Part thickness [mm]	3	2	1

Thermoset process chain – evaluation of different optimization measures

Table 50: Thermoset material manufacturing parameters for the different optimization measures

PAN fiber production										
	V1	V2	SZ1	SZ2	V3	SZ3	SZ4	SZ5	SZ6	V4
Source electricity	Grid mix	Hydro power	Hydro power	Grid mix	Grid mix	Grid mix	Grid mix	Grid mix	Grid mix	Hydro power
Base country	Japan									
Carbon fiber production										
	V1	V2	SZ1	SZ2	V3	SZ3	SZ4	SZ5	SZ6	V4
Electricity source	Grid mix	Hydro power	Grid mix	Hydro power	Grid mix	Grid mix	Grid mix	Grid mix	Grid mix	Hydro power
Base country	Global$^{1)}$	USA	Global$^{1)}$	USA	Global$^{1)}$	Global$^{1)}$	Global$^{1)}$	Global$^{1)}$	Global$^{1)}$	USA
Amount of required energy	100%	100%	100%	100%	50%	100%	100%	100%	100%	50%
Fiber type	HT									
Mass losses	~ 50 % from PAN to carbon fiber									
Matrix production										
Base country	EU-28									
Type	Epoxy									

Table 51: Production parameters for the evaluation of different optimization measures for thermoset process chains in chapter 6.3

Constant parameters			
General parameters			
Base country	Germany	Utilization rate of press	80%
Fiber density	1.78 g/cm^3	Demolding time	10 s
Resin type	Epoxy resin	Tool mounting time	4 h
Resin density	1.17 g/cm^3	No. of working days per week	5 days
Fiber volume content	50%	No. of hours per shift	8 h
Part size	1 m^2	Cut-offs final machining	10%
Part thickness	2 mm	Milling speed	1.4 m/min
Preforming			
Stack manufacturing (only required for NCF)		3D preforming	
Coverage degree 2D cutter	100%	IR heater temperature	200 °C
Cutting speed	10 m/min	IR heater size	6 m^2
Dry-Fiber-Placement (only required for DFP)		Distance between heater/preform	100 mm
Share of “on surface” time on layup time	70%	IR heater	Heating from both sides
Share of “off surface” time on layup time	30%	Process time	30 s
Layup rate	25 kg/h	Process pressure	5 bar
Head layup width	200 mm	Preform trimming (3D)	
Roving type	24k	Robot type	KR180 | KR210
Layup system	Machine type 1	Weight end effector	< 70 kg
Layup orientation	30°	Cutting speed	10 m/min
HP-RTM			
Self-heated tooling		High pressure injection device	
Tooling mass to part size	7153 kg/m^2	Resin temperature before injection	60 °C
Tooling temperature	120 °C	Temperature of hardener before injection	35 °C
Process pressure	80 bar	Resin output rate	2 kg/min
Tool changes per week	1	Vacuum pump pumping speed	120 m^3/h
No. of shifts per day	2		
Tool heating	Daily		

Varied parameters	**V1**	**V2**	**SZ1**	**SZ2**	**V3**	**SZ3**	**SZ4**	**SZ5**	**SZ6**	**V4**
Electricity source	Grid	Wind	Grid	Wind	Grid	Grid	Grid	Grid	Grid	Wind

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	mix	energy	mix	energy	mix	mix	mix	mix	mix	energy
Preforming	NCF	NCF	NCF	NCF	DFP	NCF	DFP	NCF	NCF	DFP
Textile cut-offs	20%	20%	20%	20%	0%	20%	0%	20%	20%	0%
Preform cut-offs	20%	20%	20%	20%	5%	20%	5%	20%	20%	5%
Rest of resin	5%	5%	5%	5%	1%	5%	1%	5%	5%	1%
Textile areal weight [g/m²]	250	250	250	250	200	250	200	250	250	200
Injection-curing time [min]	10	10	10	10	5	10	10	5	10	5
Recycling of cut-offs	No	No	No	No	Yes	No	No	No	Yes	Yes

Thermoplastic process chain – evaluation of different optimization measures

Table 52: Thermoplastic material manufacturing parameters for the different optimization measures

PAN fiber production										
	V1	V2	SZ1	SZ2	V3	SZ3	SZ4	SZ5	SZ6	V4
Source electricity	Grid mix	Hydro power	Hydro power	Grid mix	Grid mix	Grid mix	Grid mix	Grid mix	Grid mix	Hydro power
Base country	Japan									
Carbon fiber production										
	V1	V2	SZ1	SZ2	V3	SZ3	SZ4	SZ5	SZ6	V4
Source electricity	Grid mix	Hydro power	Grid mix	Hydro power	Grid mix	Grid mix	Grid mix	Grid mix	Grid mix	Hydro power
Base country	Global1)	USA	Global1)	USA	Global1)	Global1)	Global1)	Global1)	Global1)	USA
Amount of required energy	100%	100%	100%	100%	50%	100%	100%	100%	100%	50%
Fiber type	HT									
Mass losses	~ 50 % from PAN to carbon fiber									
Matrix production										
Base country	EU-28									
Type	PA6									

Table 53: Production parameters for the evaluation of different optimization measures for thermoplastic process chains in chapter 6.3

Constant parameters			
General parameters			
Base country	Germany	Utilization rate of press	80%
Fiber density	1.78 g/cm³	Demolding time	10 s
Matrix system	PA6	Tool mounting time	4 h
Matrix density	1.14 g/cm³	No. of working days per week	5 days
Fiber volume content	50%	No. of hours per shift	8 h
Part size	1 m²	Rest of matrix	0%
Part thickness	2 mm	Cut-offs final machining	10%
Lifting speed of press	110 mm/s	Milling speed	1.4 m/min
Organosheet production			
Organosheet manufacturing (only required for OS)		Slitter (only required for ATL)	
Fabric areal weight	250 g/m²	Cutting speed	17 m/min
Press type	Electric heated	Original role width	300 mm
Press temperature zone 1	280 °C	Thermoplastic tape laying (only required for ATL)	
Press temperature zone 2	80 °C	Tape width	100 mm
Process pressure zone 1 |	1 | 40 bar	Layup orientation	Quasi-isotropic
Process time zone 1 and zone 2	10 min	Consolidation (only required for ATL)	
Tape production (only required for ATL)		Press type	Electric heated
Areal weight	200 g/m²	Press temperature zone 1	280 °C
Press type	Electric heated	Press temperature zone 2	80 °C
Press temperature zone 1	280 °C	Process pressure zone 1	1 bar
Press temperature zone 2	80 °C	Process pressure zone 2	40 bar
Process pressure zone 1 | 2	1 | 10 bar	Process time zone 1 and 2	1.5 min
Process time zone 1 and zone 2	20 s		
TP-Forming			
IR heater		Self-heated tooling	
Process time	1.5 min	Tooling mass to part size	7153 kg/m²
IR heater size	6 m²	Tooling temperature	80 °C
IR heater material	Metal	Process time	1.5 min
IR heater	Heating from both sides	Process pressure	8 bar

Self-heated tooling	
Tool changes per week	1
No. of shifts per day	2
Tool heating	daily

Varied parameters	**V1**	**V2**	**SZ1**	**SZ2**	**V3**	**SZ3**	**SZ4**	**SZ6**	**V4**
Electricity source	Grid mix	Wind energy	Grid mix	Wind energy	Grid mix	Grid mix	Grid mix	Grid mix	Wind energy
Organosheet production	OS	OS	OS	OS	ATL	OS	ATL	OS	ATL
Organosheet cut-offs	40%	40%	40%	40%	5%	40%	5%	40%	5%
Areal weight [g/m²]	250	250	250	250	200	250	200	250	200
Recycling of cut-offs	No	No	No	No	Yes	No	No	Yes	Yes

C.4 Boundary conditions for cost evaluation in chapter 7

NCF-RTM process chain – part-related parameters

Table 54: NCF-RTM production parameters to analyse the production costs in chapter 7 starting from page 63; general cost assumptions can be found in chapter 3.3 at page 13

Constant parameters			
General parameters			
Direct material costs		Tool mounting time	4 h
NCF textile	50 €/kg	No. of working days per week	5 days
Matrix	6 €/kg	No. of hours per shift	8 h
Binder	8 €/kg	Textile cut-offs (2D)	20%
Fiber density	1.78 g/cm³	Preform cut-offs (3D)	20%
Resin type	Epoxy resin	Rest of resin	5%
Resin density	1.17 g/cm³	Cut-offs final machining	10%
Utilization rate of press	80%	Milling speed	1.4 m/min
Demolding time	10 s	Part per year	5,000 | 75,000 | 300,000
Preforming			
Stack manufacturing		3D preforming	
Textile areal weight	250 g/m²	IR heater temperature	200 °C
Coverage degree 2D cutter	100%	IR heater size	6 m²
Cutting speed	10 m/min	Distance between heater/preform	100 mm
Preform trimming (3D)		IR heater	Heating from both sides
Robot type	KR180 | KR210	Process time	30 s
Weight end effector	< 70 kg	Process pressure	5 bar
Cutting speed	10 m/min		
HP-RTM			
Self-heated tooling		High pressure injection device	
Tooling mass to part size	7153 kg/m²	Resin temperature before injection	60 °C
Tooling temperature	120 °C	Temperature of hardener before injection	35 °C
Injection- and curing time	5 min	Resin output rate	2 kg/min
Process pressure	80 bar	Vacuum pump pumping speed	120 m³/h
Tool changes per week	1		
No. of shifts per day	2		
Tool heating	Daily		

Varied parameters	**Large, thick part; FVC 45%**	**Medium**	**Small, thin part; FVC 55%**
Fiber volume content (FVC) [%]	45	50	55
Part size [m²]	1.5	1	0.5
Part thickness [mm]	3	2	1

Braiding-RTM process chain – part-related parameters

Table 55: Braiding-RTM production parameters to analyze the production costs in chapter 7 starting from page 63; general cost assumptions can be found in chapter 3.3 at page 13

Constant parameters			
General parameters			
Direct material costs		Tool mounting time	4 h
Carbon fiber roving	25 €/kg	No. of working days per week	5 days
Matrix	6 €/kg	No. of hours per shift	8 h
Binder	8 €/kg	Textile cut-offs (2D)	0%
Fiber density	1.78 g/cm^3	Preform cut-offs (3D)	5%
Resin type	Epoxy resin	Rest of resin	5%
Resin density	1.17 g/cm^3	Cut-offs final machining	10%
Utilization rate of press	80%	Milling speed	1.4 m/min
Demolding time	10 s	Part per year	5,000 | 75,000 | 300,000
Preforming			
Braiding		Preform trimming (3D)	
Rotation speed	150 rpm	Robot type	KR180 | KR210
No. of filler yarns	32	Weight end effector	< 70 kg
No. of bobbins	64	Cutting speed	10 m/min
Robot type	KR180 | KR210		
Weight end effector	< 70 kg		
Filler yarns	Yes		
Roving type	24k		
No. of robots for braiding/handling	2		
HP-RTM			
Self-heated tooling		High pressure injection device	
Tooling mass to part size	7153 kg/m^2	Resin temperature before injection	60 °C
Tooling temperature	120 °C	Temperature of hardener before injection	35 °C
Injection- and curing time	5 min	Resin output rate	2 kg/min
Process pressure	80 bar	Vacuum pump pumping speed	120 m^3/h
Tool changes per week	1		
No. of shifts per day	2		
Tool heating	Daily		
Varied parameters	**Large, thick profile; FVC 45%**	**Medium**	**Small, thin profile; FVC 55%**
Fiber volume content (FVC) [%]	45	50	55
Part size [m^2]	1.5 (ø 150 mm)	1 (ø 92.5 mm)	0.5 (ø 35 mm)
Part thickness [mm]	3	2	1

Thermoset process chain – evaluation of different optimization measures

Table 56: Assumptions for the cost analysis of different optimization measures for curved parts in chapter 7, starting from page 63; general cost assumptions can be found in chapter 3.3 at page 13

Constant parameters			
General parameters			
Base country	Germany	Utilization rate of press	80%
Fiber density	1.78 g/cm³	Demolding time	10 s
Resin type	Epoxy resin	Tool mounting time	4 h
Resin density	1.17 g/cm³	No. of working days per week	5 days
Fiber volume content	50%	No. of hours per shift	8 h
Part size	1 m²	Cut-offs final machining	10%
Part thickness	2 mm	Milling speed	1.4 m/min
		Part per year	5,000 | 75,000 | 300,000
Preforming			
Stack manufacturing (only required for NCF)		3D preforming	
Coverage degree 2D cutter	100%	IR heater temperature	200 °C
Cutting speed	10 m/min	IR heater size	6 m²
Dry-Fiber-Placement (only required for DFP)		Distance between heater/preform	100 mm
Share of “on surface” time on layup time	70%	IR heater	Heating from both sides
Share of “off surface” time on layup time	30%	Process time	30 s
Layup rate	25 kg/h	Process pressure	5 bar
Head layup width	200 mm	Preform trimming (3D)	
Roving type	24k	Robot type	KR180 | KR210
Layup system	Machine type 1	Weight end effector	< 70 kg
Layup orientation	30°	Cutting speed	10 m/min
HP-RTM			
Self-heated tooling		High pressure injection device	
Tooling mass to part size	7153 kg/m²	Resin temperature before injection	60 °C
Tooling temperature	120 °C	Temperature of hardener before injection	35 °C
Process pressure	80 bar	Resin output rate	2 kg/min
Tool changes per week	1	Vacuum pump pumping speed	120 m³/h
No. of shifts per day	2		
Tool heating	Daily		

Varied parameters	**V1**	**V2**	**V3**	**V4**
Preforming	NCF	NCF	DFP	DFP
Direct material costs				
Textile/ Carbon fiber roving	50 €/kg	25 €/kg	20 €/kg	10 €/kg
Matrix	6 €/kg	6 €/kg	6 €/kg	6 €/kg
Binder	8 €/kg	8 €/kg	8 €/kg	8 €/kg
Credit of cut-offs	0 €/kg	0 €/kg	1 €/kg	1 €/kg
Textile cut-offs	20%	20%	0%	0%
Preform cut-offs	20%	20%	5%	5%
Rest of resin	5%	5%	1%	1%
Textile areal weight [g/m²]	250	250	200	200
Injection-curing time [min]	10	10	5	5
Recycling of cut-offs	No	No	Yes	Yes

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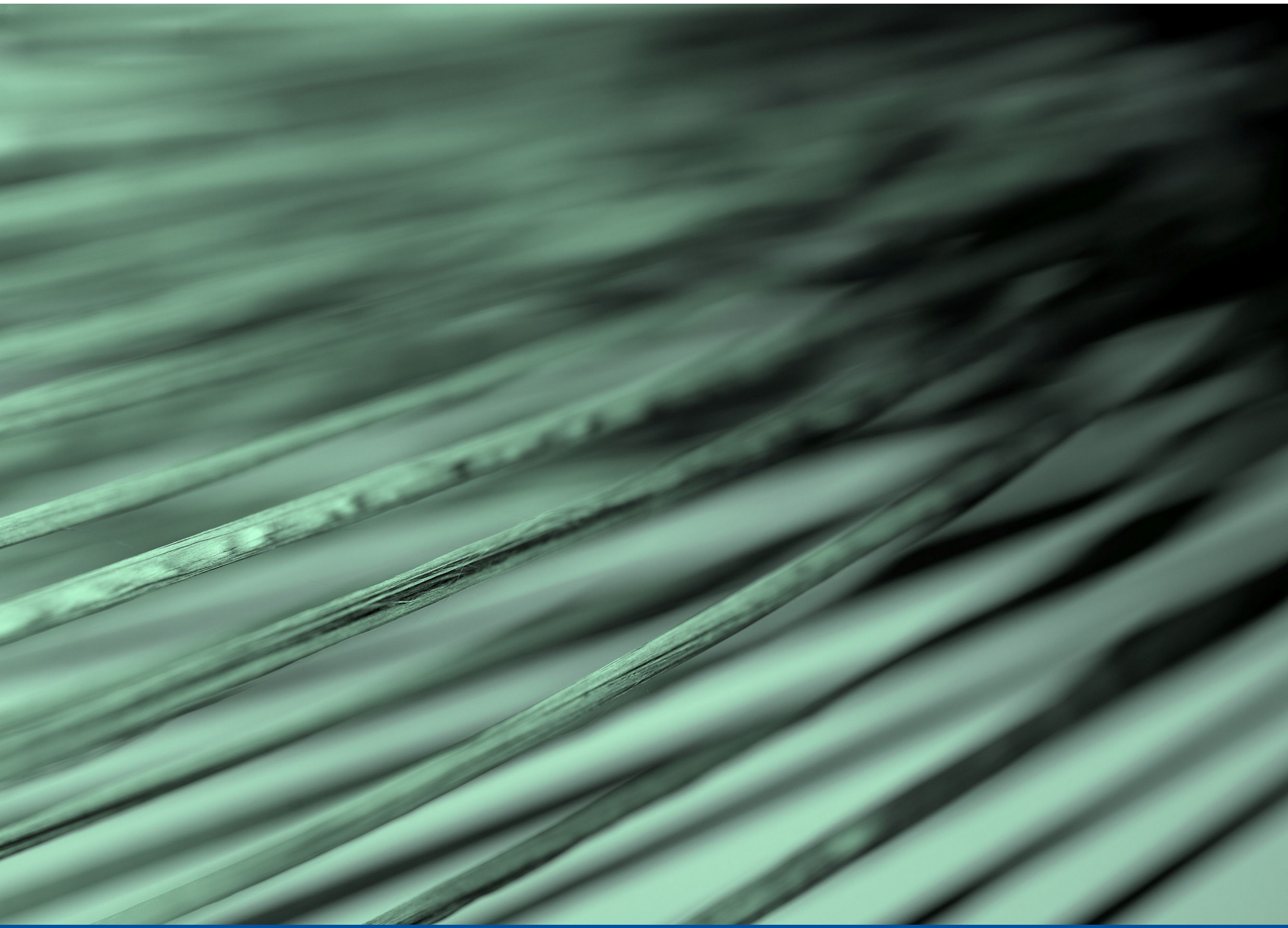

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