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PRODUCTION PROCESS

Resource efficiency and environmental impact of fiber reinforced plastic processing technologies

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Abstract

The process energy demand and the environmental indicators of two carbon fiber reinforced plastic process chains have been investigated. More precisely, the impact of different production set-ups for a standard textile preforming process using bindered non-crimp fabric (NCF) and a material efficient 2D dry-fiber-placement (DFP) process are analyzed. Both 2D preforms are activated by an infrared heating system and formed in a press. The resin-transfer-molding (RTM) technology is selected for subsequent processing. Within a defined process window, the main parameters influencing the process energy demand are identified. Varying all parameters, a reduction of 77% or an increase of 700% of the electric energy consumption compared to a reference production set-up is possible, mainly depending on part size, thickness, and curing time. For a reference production set-up, carbon fiber production dominates the environmental indicators in the product manufacturing phase with a share of around 72–80% of the total global warming potential (GWP). Thus, the reduction of production waste, energy efficient carbon fiber production, and the use of renewable energy resources are the key environmental improvement levers. For the production of small and thin parts in combination with long curing cycles, the influence of the processing technologies is more pronounced. Whereas for a reference production set-up, only 10% (NCF–RTM) and 15% (DFP–RTM) of the total GWP are caused by the processing technologies, a production set-up leading to a high process energy demand results in a share of 40% (NCF–RTM) and 49% (DFP–RTM), respectively.

Keywords Carbon fiber reinforced plastics (CFRP) · Life cycle assessment (LCA) · Energy analysis · Dry-fiber-placement (DFP) · Resin-transfer-molding (RTM)

1 Introduction

Wherever masses are required to be moved the excellent weight-specific performance of carbon fiber reinforced plastics (CFRP) results in energy, fuel and emission savings during the use phase of a product. The actual sustainability benefits of these materials depend on the manufacturing chain, the achieved weight reduction and the respective application. In the aviation industry, the use of lightweight structures leads to significant fuel savings throughout the use phase. By a weight reduction of 1 kg for example, the annual kerosene consumption can be reduced by 200 l on average [1]. Thus, an environmental benefit can be claimed after 10,000 km using CFRP instead of steel, even though the environmental impact in the production phase is increased [1]. In another study [2] addressing applications in the field of mechanical engineering, a weight reduction of about 90% compared to an aluminum tool is achieved. Here, an environmental benefit of the investigated self-heated CFRP curing tool could already be realized in the production phase. During the use phase, another 85% of the electrical energy demand can be saved. In the automotive industry, fuel savings gained through weight reductions are considerably lower than in the aviation industry. Consequently, the

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environmental impacts of the production phase, the achieved weight reduction and the resulting fuel savings have a significant impact on the environmental benefit of a lightweight design throughout the lifetime. Studies indicate that under certain conditions a reduction of the environmental impacts is possible over the entire life cycle of a CFRP structure [3–8]. Yet, based on different assumptions and varying boundary conditions, published results greatly diverge. While for example in Duflou et al. [3] the substitution of a steel body-in-white (BIW) with a CFRP structure results in a lower environmental impact after 132,000 km, in Das [4] however, there is no break even, even after 200,000 km compared to the steel version. In a further study [7] the environmental benefit of different lightweight materials (steel, aluminum, CFRP) for automotive applications is investigated. However due to the large spread of the environmental burden in the manufacturing phase of a CFRP structure, no clear statement is given. Based on these results, the environmental impact of different energy and technology related optimization measures in the production phase are explored [9]. It is shown that the total environmental impact of CFRPs is dominated by the carbon fiber production. Thus, technological improvements like the reduction of production waste, the recycling of cut-offs, and the use of renewable energies lead to environmental benefits.

The present work is a continuation of this study [9], focusing on the influence of different part geometries and processing parameters on the energy demand and the resulting environmental impacts. The aim of these investigations is to show, whether the production set-up can have a relevant impact on the environmental burden of a CFRP structure. First, the investigated process chains, a standard textile process and a material-efficient lay-up technology, are briefly described. Second, the applied methods as well as all relevant boundary conditions for the energy analysis and the life cycle assessment are presented. Subsequently, the results are shown and discussed in detail. For each process chain, the impacts of different production scenarios are evaluated and compared within that specific process chain. In the last chapter, all results are summarized and several recommendations are given.

2 Overview of the investigated technologies

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. Non-crimp-fabrics (NCF) are often the material of choice, due to the better mechanical properties in contrast to woven fabrics [10]. 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% can occur, depending on part size and textile roll, even though modern nesting programs can reduce the production waste [11].

A load-path adapted and material-efficient lay-up can be realized by automated fiber placement (AFP) technologies. In the aviation industry, AFP processes are already applied for a couple of years for the production of primary structures (fuselage, frame) [12–14]. In order to realize the required production rate for the automotive industry, the process chain must be automated in a number of key steps and adapted to the processing of cheap semi-finished textiles. In the last years, various placement technologies were developed for low-cost processing of rovings, binder yarns and TowPregs. To allow comparability, this study focuses on 2D dry-fiber-placement (DFP) technologies. Depending on the type of lay-up technology, 8–16 binder yarns or spread carbon fiber rovings can be fed and cut individually. The majority of currently available systems on the market are robot-based. The fixation of the tows can be realized through continuous activation of the binder either with an infrared heating lamp or a laser source during lay-up, and the spread rovings are adhesively fixed at the edges of each course [11, 15].

To obtain a 3D preform, an additional forming step is necessary. 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 where the binder is allowed to solidify. Afterwards the preform is trimmed using e.g. a stamping tool or a robot-based supersonic cutting device.

In the automotive industry, Resin-transfer-molding (RTM) is, apart from wet compression molding, the most commonly used technology for the production of high-performance composite structures. 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. Self-heated tools (usually with water as heat transfer medium) with curing temperatures ranging between 80 and 130 °C are typically used [15].

Usually, the parts have to be machine finished, even though a near-net shape preforming technology is used. In this work, a state of the art milling technology is considered to realize the final geometry. All subsequent process steps, i.e. surface treatment for painting or bonding are excluded.

Please note that no comparison is drawn between the products of the NCF–RTM and DFP–RTM process chains. They are used as examples for process chains with high and low cut-offs, and both are scaled to 1 kg CFRP part. However, these parts are not functionally equivalent as they would have entirely different geometries and purposes in a more complex product (e.g. an automobile chassis).

3 Method

To quantify the resource consumption and the environmental impact of the processes, products and services, the method of life cycle assessment (LCA) according to DIN EN ISO 14040 and DIN EN ISO 14044 [16] is often applied. Considering the life cycle point of view, LCA allows taking into consideration all resources used, all emissions released, 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. The quality and reliability of a LCA strongly depend on the underlying data. For well-established materials, high quality data sets (provided e.g. by PlasticsEurope, International Iron and Steel Institute IISI) are available to track the environmental interactions across the life cycle of a product. Looking at the manufacturing of high-performance composite structures, however, only a small fraction of life cycle inventory (LCI) data sets exists. In addition, it is not clear on which production parameters these data sets are based. In this study, two interrelated methods are applied to evaluate the resource efficiency of CFRP processing technologies.

3.1 One-factor-at-a-time (OFAT) analysis for the energy consumption

The 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 set-ups. In addition the results are used for a sensitivity analysis pointing out the impact of different process parameters on the energy demand.

Measurements were taken with varying part complexities and process parameters. The energy data were gained from three 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 set for a compressor with medium electricity consumption is adopted [17]. An overview of all measured production scenarios for each process technology used in the investigated production chain can be found in [15]. The development of the empirical models based on the measured data is explained in detail in [15] as well. The weight-specific process energy demand is related to the respective semi-finished product 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. To estimate the process energy demand for all production technologies of the respective process chain, the material flows are considered. For the final energy analysis, more than 20 parameters are varied within a defined process window. Hereby only one factor at a time is changed, while the others remained on the medium set-up. Note that 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. In this regard, some of these combinations strongly depend on the used resin system, as this usually defines the required temperature, pressure and curing cycle. The production set-ups within the process window are realistic for industrial production. However, to apply the results in practice, a critical check of the underlying process parameters and the specific production set-up (application, part, material, etc.) is recommended. In this study the maximum fluctuation is used as best/worst-case scenario to prove whether the production set-up can have an impact on the environmental burden and thus has to be considered in future assessments.

3.2 Life cycle assessment to evaluate the environmental impacts

For this work, a cradle-to-gate analysis following DIN EN ISO 14040 and DIN EN ISO 14044 was performed. The LCA study is broken down into four phases, conforming to the ISO standards. The first two phases—the definition of goal and scope as well as the LCI—are described in the following. The life cycle impact assessment and the discussion of the results are presented in separate sections.

Goal and scope contains the specification of all relevant boundary conditions for the analysis, as well as the functional unit to which all results refer to. The focus of this work is to identify the main influences on the process energy demand and the resulting impact on the environmental indicators for the production of 1 kg CFRP. Thus, the functional unit is related to a defined mass, i.e. any possible impact on the performance due to a different production set-up is not considered. Besides that, the environmental burden is dominated by the carbon fiber production. The influence of the process energy demand in the manufacturing phase therefore depends on the required amount of material for the production of 1 kg CFRP. This fact is taking into account as two process chains with varying cut-off rates are investigated. However a product specific comparison of the process chains is not part of the study. The use phase and end of life are excluded from the assessment (this constitutes a "cradle to gate"). Also, the transportation of the carbon fibers is neglected in the balance.

All other important system boundaries are listed in Tables 1 and 2. The LCA was performed using the GaBi ts software version 8.1.0.29, data base version 8.6 SP33.

The life cycle inventory contains all material and energy flows required to provide the functional unit in the defined technical systems. In the resulting mass and energy balance (LCI results) all resource extractions from the environment are listed on the input side. The occurring emissions to air, water and ground are on the output side. For the data provision the balance model can be divided into a technical foreground and background system, compare Fig. 1 and Albrecht et al. [24].

Material and energy flows in the foreground system are usually defined through intermediate products, e.g. the amount of electricity or resin. The background system links those data with the corresponding resources and emissions, which are either taken from or released to the environment. For all background data (energy supply, PAN-fiber production, epoxy resin, etc.) the GaBi Professional database containing all corresponding resources and emissions is used. The respective datasets are shown in Table 1.

For the foreground data, both an intensive literature survey was performed and the mass and energy flows for different process technologies were measured. More than 15 studies containing relevant data for the production of CFRP structures were found in over 50 screened sources [3–5, 8, 25–36]. Particularly for the carbon fiber (PAN to CF) and textile (fabric, NCF) production, as well as the machining [15], LCI data representing industry standards were determined and evaluated in close cooperation with an industrial advisory board comprising AUDI, BASF, Benteler-SGL, BMW, CarboNXT, SGL-Group and TohoTenax. In addition to the intermediate products of the background system, as shown in Fig. 1, released emissions from carbon fiber production were taken into account.

In contrast, reliable data for different preforming, curing and thermoforming technologies are hardly available. Furthermore, the corresponding production scenarios are often not documented. Therefore, different process technologies were investigated and the process energy demand was determined by measurements under varying process conditions (OFAT energy analysis). In addition to the energy and compressed air demand, the cooling water consumption was measured. Possible emissions, including particulate matter, occurring in the preforming, curing and finishing steps were neglected.

For the life cycle impact assessment the CML method by the University of Leiden was selected. A broad range of impacts are evaluated. However, only the primary energy demand (PED) and the global warming potential (GWP) are illustrated and discussed in this paper. GWP is the most frequently used indicator in any environmental assessment, while PED addresses energy resources, which is arguably one of the most relevant issues in CF production. The two indicators are related, but not interchangeable. The GWP addresses emissions related to anthropogenic climate change that are released from the product system, i.e. carbon dioxide CO_2, methane CH_4, and nitrous oxide N_2O, among others. The (fossil) PED addresses the energy content of (fossil) resources fed into the product system, i.e. crude oil, hard coal, lignite etc. Where these resources are used for energy generation, the PED is closely connected to the GWP. However, the GWP/PED ratio varies between different resources

Table 1 Global boundary conditions for the eco-balancing of 1 kg CFRP

Parameter	Specification	Remarks
PAN-fiber production		
Base country	Japan	Dataset in GaBi professional database [18], 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 [19] using the corresponding energy generation datasets in GaBi professional database [20]
Type	HT fiber	
Mass losses	~50% from PAN to carbon fiber	
Fiber density	1.78 g/cm^3	
Matrix		
Base country	Europe	Available dataset in GaBi professional database [21]
Type	Epoxy resin	
Matrix density	1.17 g/cm^3	
Part production (2D preforming, 3D preforming, RTM)		
Base country	Germany	Available dataset for electricity mix [22], pressurized air 7 bar (mean consumption) [17] and cooling water in GaBi professional database [23]

Table 2 Scenario specific boundary conditions for a low, medium and high process energy demand

Constant parameters for the material flow, cut-offs are relative to the input	NCF–RTM	DFP–RTM
2D cuttings [%]	20	0
3D cuttings [%]	20	5
Matrix waste [%]	5	5
Machining cuttings [%]	10	10
Fiber volume content [%]	50	50

Variable parameters during part production	NCF–RTM			DFP–RTM		
	Low	Medium	High	Low	Medium	High
Textile areal weight [g/m^2]	500	250	125	250	200	150
Part size [m^2]	1.5	1.0	0.5	1.5	1.0	0.5
Part thickness [mm]	3	2	1	3	2	1
Cutting speed [m/min]	20	10	5	20	10	5
Lay-up rate [kg/h]	–	–	–	50	25	10
Lay-up width of head [mm]	–	–	–	300	200	100
Roving type	–	–	–	50 k	24 k	12 k
DFP fixation system	–	–	–	IR	Adhesive	Laser
Lay-up orientation (average) [deg]	–	–	–	0	30	60
Infrared heater temperature [°C]	150	200	250	150	200	250
Infrared heater size [m^2]	4	6	8	4	6	8
Distance preform to heater [mm]	80	100	150	80	100	150
Heating and draping time [s]	20	30	50	20	30	50
Draping pressure [bar]	2.5	5	10	2.5	5	10
Utilization of press size area [%]	100	80	50	100	80	50
RTM tooling mass/part size [kg/m^2]	4333	7153	10,000	4333	7153	10,000
Tooling temperature [°C]	80	120	140	80	120	140
Tool heating to isothermal dwell temperature	Daily	Daily	Once a week	Daily	Daily	Once a week
Injection and curing time [min]	3	5	10	3	5	10
Injection pressure [bar]	40	60	80	40	60	80
Resin injection temperature [°C]	35	60	80	35	60	80
Resin injection output rate [kg/min]	4	2	1	4	2	1

Table 2 (continued)

Variable parameters during part production	NCF–RTM			DFP–RTM		
	Low	Medium	High	Low	Medium	High
Pumping speed vacuum pump [m^3/h]	10	120	260	10	120	260
Number of tool changes per week	1	1	5	1	1	5
Number of shifts per day	3	2	1	3	2	1

(e.g. electricity from natural gas releases less CO_2 per kWh than electricity from lignite). Where oil is used as a material resource to produce monomers for plastics, the PED is disconnected from the GWP (unless the material is combusted at its end of life, which is excluded in this study). The PED of CFRP parts is related to both energy and material use of resources by varying degrees, depending on the specific part and manufacturing technology.

4 Results

For both evaluation methods, the material flow has to be considered to evaluate the data and to generate the results. An overview for a standard textile preforming process chain and a material-efficient lay-up technology is given in Fig. 2. In this regard the aim of this study is to prove, whether the process parameters and part size, resulting in different process energy demands, have an impact of the environmental burden of a CFRP structure. To ensure a systematic comparison, the material flow for each process chain is fixed. However depending on part geometry and textile roll width, the amount of cut-offs can greatly vary during textile tailoring and 3D preform trimming. Therefore an additional sensitivity analysis is performed. For the final evaluation, an average cut-off during 2D and 3D preforming of 20% is used, defined through the advisory board. A DFP technology, which enables an individual feeding and cutting of each roving, can significantly improve the material efficiency. Assuming an optimal design of the 2D stacking with respect to the forming behavior, only 5% of the material input has to be cut-off for the RTM tool.

For each process chain, a finishing step through milling/assembly is further considered, where a 10% cut-off is assumed. Additionally, a marginal difference in the required resin amount for both process chains is visible in Fig. 2. Explanations can be found in the different materials added to the preforms: Whereas a DFP preform contains only a binder and the fibers, a NCF preform requires the incorporation of a binder and sewing thread. A detailed overview of all parameters relevant for the material flow and the process energy demand is given in Table 2.

4.1 OFAT analysis for process energy consumption

The OFAT analysis involves the variation of each process parameter within a defined process window as well as the evaluation of the resulting impact on the weight specific process energy demand. Interactions of individual process parameters are not subject of this study. The process energy demand incorporates electricity and compressed air for the processing technologies. The energy consumption required for the material production (carbon fiber and resin) is not

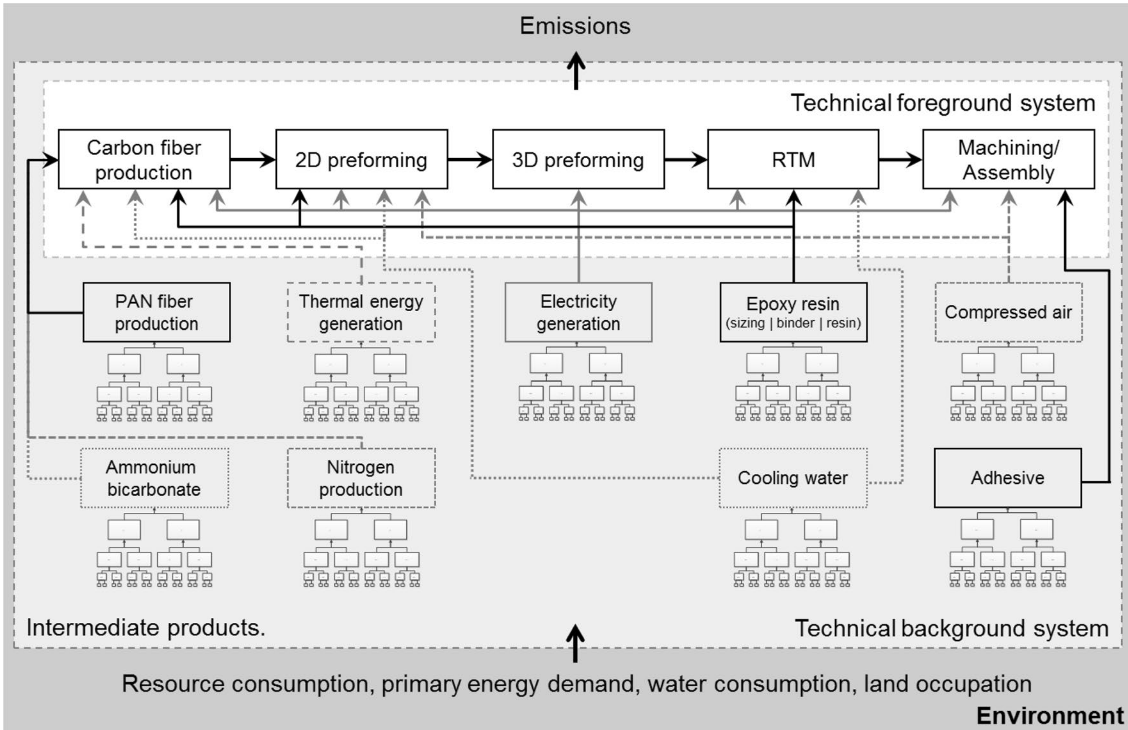

Fig. 1 Technical foreground and background system in the life cycle inventory

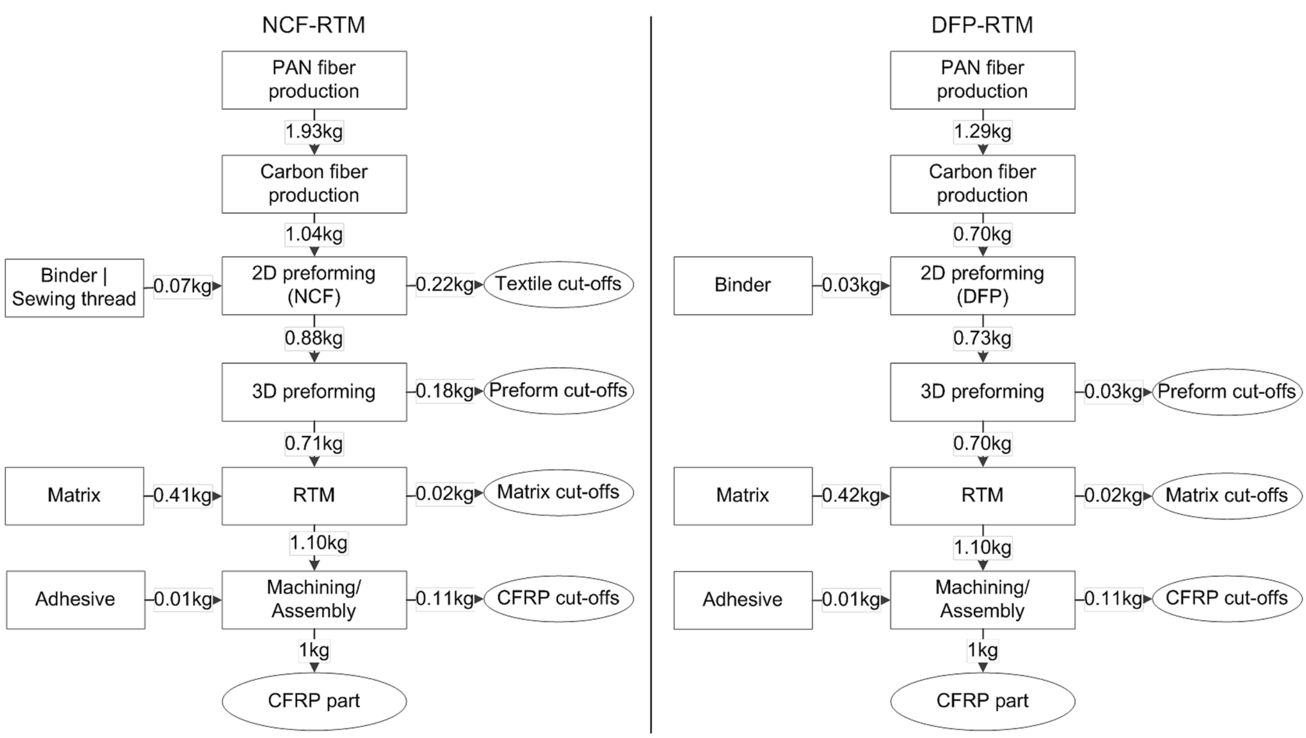

Fig. 2 Material flows for both investigated process chains

considered in the OFAT analysis. Also the fiber volume content (FVC) and the cut-offs for each process chain remain unchanged for the final investigations to ensure a systematic comparison of the different production scenarios. To address part geometry induced cut-off variations, a separate sensitivity analysis was performed before. Halving and doubling the averaged preforming cut-offs for both process chains leads to a change below 10% of the weight-specific process energy demand.

An overview of the process window for the final evaluation is given in Table 2. The column labels low, medium and high refer to the calculated process energy demand and the corresponding environmental impacts.

The times for tool mounting, preform handling and demolding is also considered but kept constant for all scenarios. Up-scaling effects, e.g. infrared heating for lay-up width increase from 100 to 300 mm are not considered. The main difference between the NCF–RTM and DFP–RTM process chains are the cutting rates, resulting in different material flows (compare Fig. 2). The textile/fiber areal weight is also varied in a different range. A NCF usually consists of at least two layers, with a consistently higher areal weight than for one layer placed with a DFP process. For the medium set-up the shares of process energy demand for the respective process steps are investigated. Even if the process parameters for the NCF–RTM and DFP–RTM process chains are identical regarding the 3D preforming, curing and finishing step, a different share of the process energy demand is calculated. This is due to two differences between NCF and DFP processes: First, the NCF–RTM process chain needs more material to be formed due to the higher amount of cuttings. Second, the DFP process is a more complex and energy intensive process than the textile production. In Fig. 3 the shares of the process steps for both process chains are presented. As expected, the DFP process has a higher energy demand than the NCF production. Therefore, the shares of the 3D preforming, RTM, and finishing are slightly lower. However, in both process chains the RTM process clearly dominates the process energy demand with a share of 52–59% of the total process energy demand.

Within both process chains, more than 20 parameters are varied and the impact on the weight specific process energy demand is investigated. The medium production set-up is chosen as a baseline for comparisons (compare Table 2). The results of the OFAT analysis for the NCF–RTM process chain are presented in Fig. 4. Only the parameters with an impact higher than 10% of the energy demand are shown due to the large number of parameters.

Combining all parameters resulting in a low process energy demand, a total reduction of more than 72% compared to the medium production set-up was calculated with the empirical model. The worst-case scenario results in around 700% (almost eightfold) increase of the process energy demand of 1 kg CFRP. The main influencing parameters are part size and thickness, as well as the curing time. Possible case specific and individual interactions between parameters (e.g. lower part thickness or smaller part size might lead to lower curing times) are not considered. However, 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 increasing the curing temperature as the impact of a temperature increase is far below 10%.

The results of the OFAT analysis for the DFP–RTM process chain are very similar, see Fig. 5. The weight specific process energy demand varies between 77% reduction and around 615% (sevenfold) increase compared to the baseline. Main influence parameters are again the part size, the part

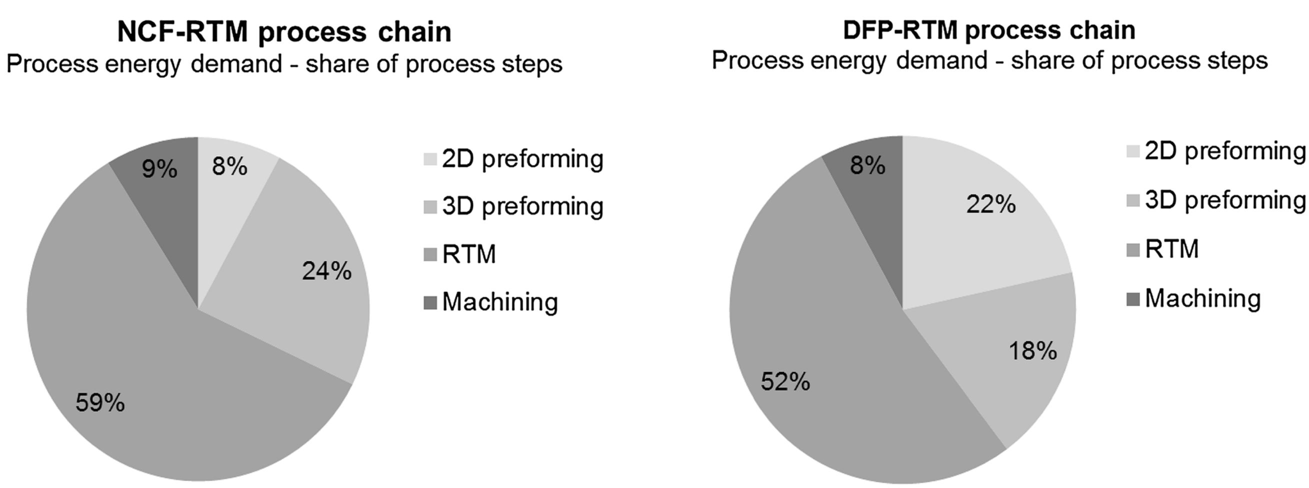

Fig. 3 Process step share of the process energy demand for the production of 1 kg CFRP (process energy demand for carbon fibers and matrix is not considered)

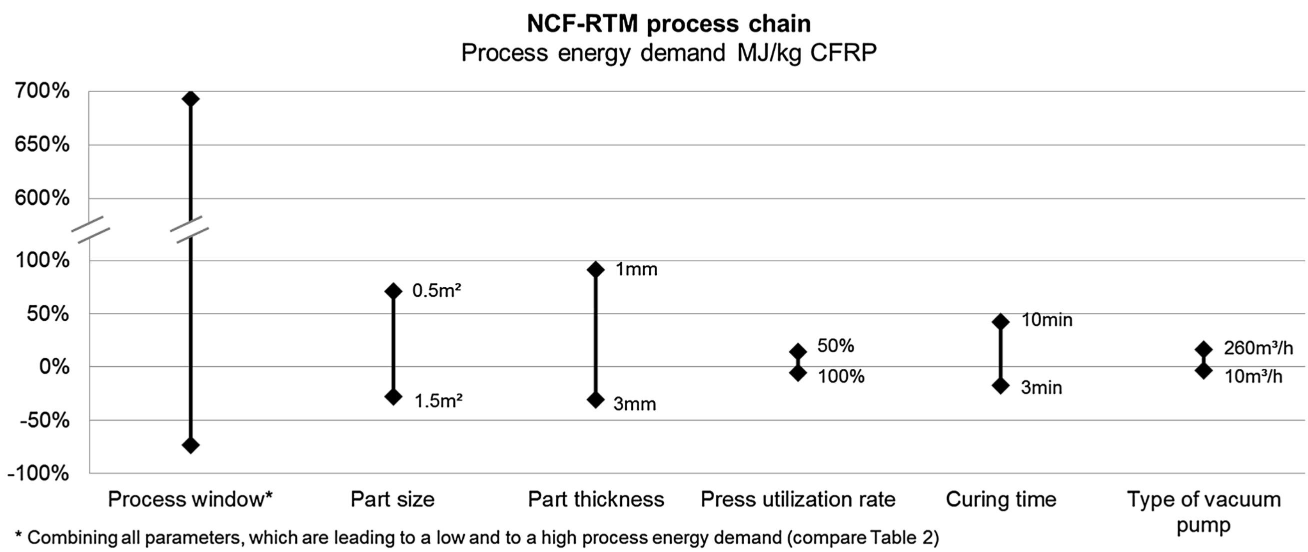

Fig. 4 OFAT—energy sensitivity analysis for the NCF–RTM process chain (process energy demand for carbon fibers and matrix is not considered)

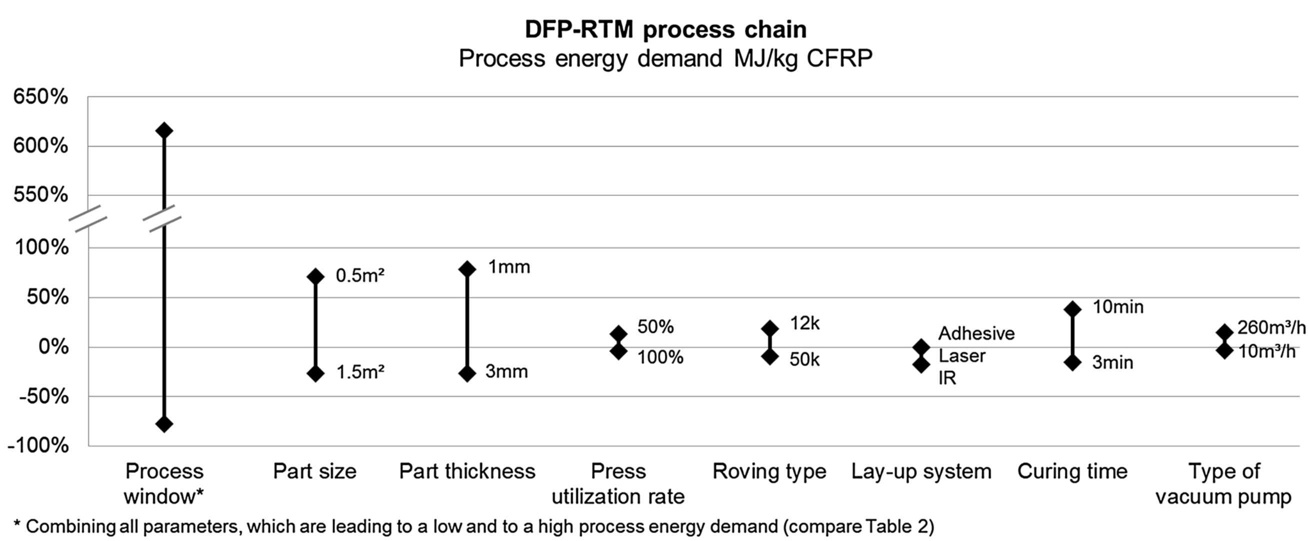

Fig. 5 OFAT—energy sensitivity analysis for the DFP–RTM process chain (process energy demand for carbon fibers and matrix is not considered)

thickness and the curing time, followed by the roving type, which has a slightly higher impact than the lay-up system. In contrast, the influence of the lay-up rate on the total process energy demand is marginal ($<10\%$). The total process energy demand of the DFP process is dominated (with over 60%) by the compressed air consumption. For a medium production set-up, an adhesive fixation is chosen. Hereby, the compressed air consumption does not depend on the process time but on the number of parallel-fed rovings [15]. Hence, a higher lay-up rate leads to lower electrical energy demand per kilogram placed preform, while the dominating compressed air consumption remains unchanged.

4.2 Life cycle impact assessment

In contrast to the OFAT analysis, the cradle-to-gate LCA takes into consideration all material and energy flows required for the production of 1 kg of a CFRP part. The results for two environmental indicators PED and GWP are presented in Figs. 6 and 7. The impact of different production set-ups with average cut-off rates for a standard textile (NCF) and a material-efficient placement technology is compared in both impact categories. As depicted in Fig. 6, it can lead to a total increase of 37% (PED) to 50% (GWP) for the NCF process chain.

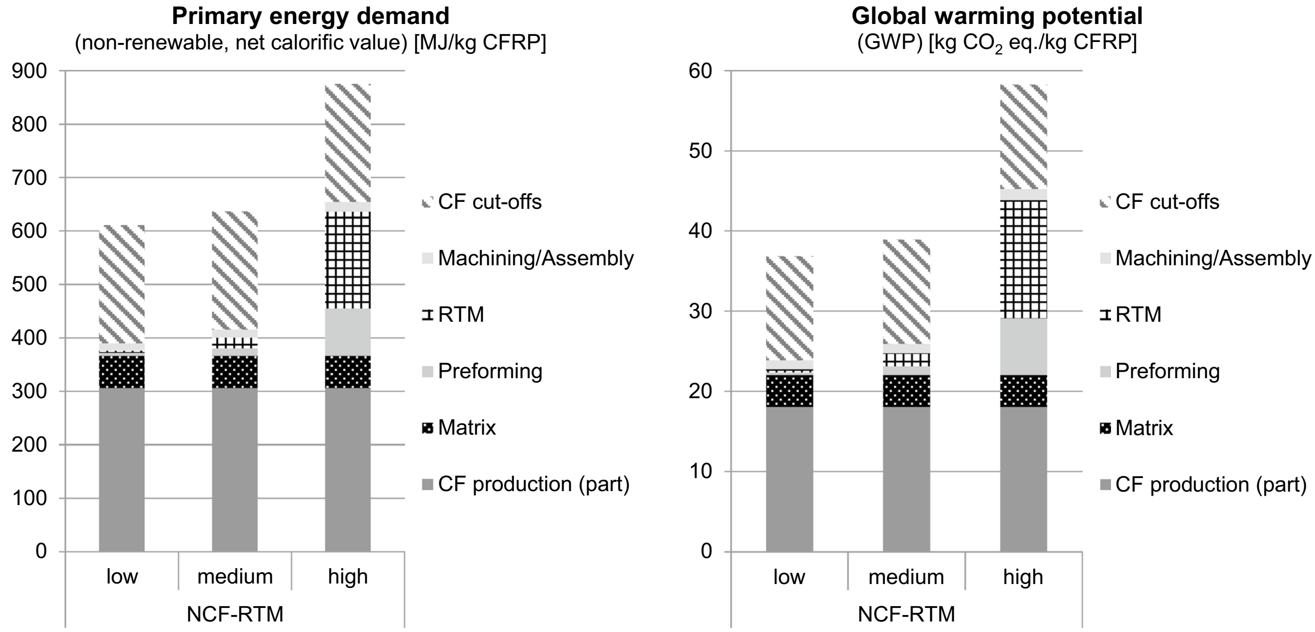

Fig. 6 Environmental impacts (PED, GWP) of the NCF–RTM production scenarios resulting in a low, medium and high process energy demand (see Table 2)

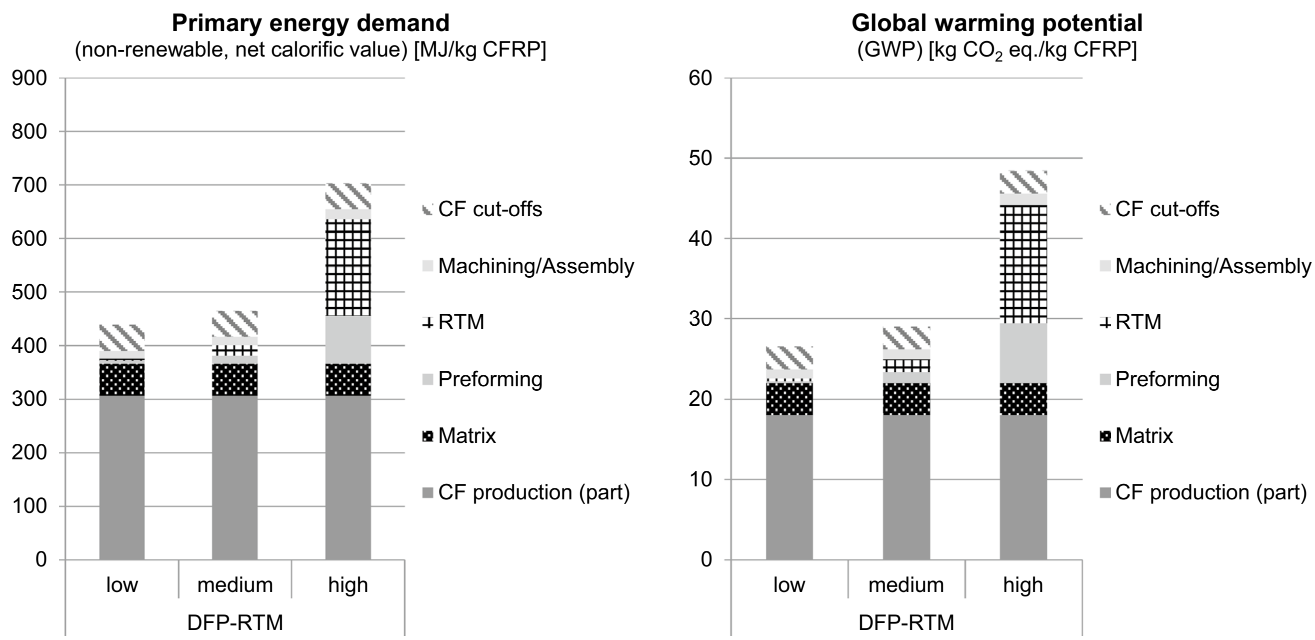

Fig. 7 Environmental impacts (PED, GWP) of the DFP–RTM production scenarios resulting in a low, medium and high process energy demand (see Table 2)

Furthermore, the environmental footprint of carbon fiber production is divided into carbon fiber remaining in the part and carbon fiber cut-offs. It can be observed that the cut-off rates have a considerable influence on the respective footprint. Consequently, the impact of the production set-up is higher for lower cut-off rates. Changes induced through part geometry, e.g. doubled cut-offs, result in a decreased influence of the production set-up. For the NCF–RTM process chain, only a 37% change of the GWP between the medium and the high production set-ups is observed. In contrast, by halving the cut-offs, the GWP varies from 30 to 52 kg CO_2eq per kg CFRP.

This is enhanced when a material-efficient preforming technology is applied. Figure 7 shows a 50% (PED) to 67% (GWP) increase related to a medium production set-up.

Furthermore, Figs. 6 and 7 show that the share of process steps on the environmental impacts changes. The percentage distribution of the GWP for each production set-up is given in Table 3. Whereas for a medium production set-up, the total carbon fiber production (CF production for the part and CF cut-offs) has a share of around 72% for the DFP–RTM process chain, a production set-up resulting in a high process energy demand leads to an increased share of the processing technologies. Instead of 15%, around 50% of the GWP for 1 kg CFRP are attributed to the processing technologies—preforming, RTM, machining. The influence of the carbon fiber production (part and cut-offs) decreases to 43%. A similar shift is visible for the NCF–RTM process chain. The impact share of the carbon fiber production in the GWP for 1 kg CFRP decreases from around 84% for a low energy set-up to 53% for a high energy set-up.

5 Conclusion

In this study, the energy efficiency of two different CFRP process chains is investigated and influences on the environmental indicators are evaluated. The results show, that especially part size and part thickness strongly influence the weight specific process energy demand of part manufacturing. Considering all 20 varied parameters the process energy demand for the production of 1 kg CFRP fluctuates within the process window between a possible reduction of around 77% and a 700% increase compared to a medium set-up. Hereby, only the processing technologies and not the material production itself are considered. In both investigated process chains, the dominating production step regarding the weight specific process energy demand is the RTM process.

The life cycle assessment confirms the huge influence of the carbon fiber production on the environmental burden of a CFRP structure. Moreover, it is shown that a production set-up resulting in a high process energy demand, can lead to a significant increase across all considered environmental indicators. However the production set-up induced changes depends on the considered cut-off rates. Whereas the process parameter variation for a NCF process chain with 20% cut-offs at each preforming step results in an increase of 50%, the changes for a material-efficient process chain leads to 67% higher GWP compare to a production set-up with a medium process energy demand. Conversely, the carbon fiber production with a share of around 72–80% for a medium production set-up is less dominant; only 43–53% of the GWP for 1 kg CFRP are caused by the carbon fiber production. The reduction of the cut-offs and the use of renewable energy in carbon fiber production still offers the greatest potential to improve the environmental impacts of both, carbon fiber and CFRP parts. Taking into account that part size and thickness, which have the main impact on the weight specific process energy demand, are usually defined by the required performance, the highest process energy reduction potential lies in the curing time. Curing time reductions, e.g. through an increase of tooling temperature, could lead to relevant process energy savings especially for small and thin parts. Nevertheless, the study shows that for an environmental evaluation of CFRP parts, in particular the part size and thickness need to be considered. Therefore, a parametric unit process model, taking into account the dominant part features, determining the impact per kg of output material should be used in future LCA studies of CFRP parts. Further studies can then focus on the individual interactions between parameters for example to quantify the reduction potential of different measures processing a small, thin part and the resulting environmental impacts.

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Table 3 Distribution of the impact category GWP along the process chain

GWP	NCF–RTM			DFP–RTM		
	Low	Medium	High	Low	Medium	High
Total CF production	84	80	53	79	72	43
CF production (part)	49	47	31	68	62	37
CF cut-offs	35	33	22	11	10	6
Matrix	11	10	7	15	13	8
Preforming	1	3	12	1	5	15
RTM	1	4	25	1	6	31
Machining/assembly	3	3	3	4	4	3

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