Supplementary material

Can carbon fiber composites have a lower environmental impact than fiberglass?

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1. Upscaling and adaptation in bio-based carbon fiber production

Data for the production the lignin- and bio-polyurethane based fibers were collected within the LIBRE (2016) project. Two processes were upscaled to industrial level or adapted to better fit lignin's inherent properties: the precursor fiber spinning and the stabilization and carbonization process.

1.1 Precursor fiber spinning

The data collected for the precursor fiber spinning were for a pilot scale process. The different parts of the precursor fiber spinning process included drying of the pellets, heating of the machine, processing, and cleaning of the machine. When upscaling to industrial scale, the data related to drying of the pellets, heating of the machine and cleaning was left unchanged, but the data related to processing were changed to be the value for lignin precursor fiber spinning suggested by (Das, 2011) which corresponds to 0.1 kwh/kg precursor fiber, and we assume that the energy carrier is electricity. Not that the value suggested by Das (2011) is for the total energy consumption for melt spinning, but we chose this value for upscaling for the processing only due to uncertainties in what is included or not, which means that there could be some overlapping and double counting. This means that in reality, the value for only the processing of the fiber could be lower thus resulting in a lower precursor fiber spinning energy use.

1.2 Stabilization and carbonization

Data for stabilization and carbonization were obtained for PAN-based carbon fibers. Das (2011) means that the inherent properties of lignin can lead to the oxidation and carbonization of the lignin- precursor fiber could require 25% less energy than the conversion of PAN. He writes that this is a consequence of the oxygenated nature of lignin which could lead to less time at the stabilization steps as well as lignin's high level of aromatic compounds that could lead to a lower time for carbonization. It is not known to which extent the blend with bio-polyurethane would influence this possible energy reduction, but in this study, for simplicity reasons, it is assumed to be negligible. Therefore, the lignin- and bio-polyurethane based precursor fibers are assumed to require 25% less energy in the stabilization and carbonization phase than the PAN-based carbon fibers. We assume that this reduction in energy needed for the lignin-based carbon fibers compared to the PAN-based carbon fibers applies both to carbon fiber production by means of furnaces and by means of microwave technology.

2. Allocation

2.1 Lignin production

The values used for calculating the economic allocation factors is found in Table S1and the allocation factors are found in Table S2. The mass output of the system is based on the data provided by Moncada et al. (2018) (their "system I").

Table S1: The prices of the outputs from the lignin production system

Output	Price per kg	Reference
Lignin	0.3 €	González-García et al. (2016)
C6 sugars	0.3 €	Moncada et al. (2018)
Furfural	0.9 €	Moncada et al. (2018)

The economic allocation factors are calculated using Equation S1

$$a_e = \frac{mass\ of\ product\ a * price\ of\ product\ a}{price\ of\ total\ output} \quad \text{(Eq. S1)}$$

Table S2: Allocation factors used in the allocation for lignin production

Product	Allocation factors
Hexose	0.61
Furfural	0.06
Lignin	0.33

As a proxy for a future where the demand, and thus the price of lignin, increases significantly compared to the other co-products, the main product bears all burden approach as suggested by Sandin et al. (2015) was used. The allocation factors can be found in Table S3.

Table S3: Allocation factors used in the allocation for lignin production when demand for lignin increases

Product	Allocation factors
Hexose	0
Furfural	0
Lignin	1

2.2 Recycling

In this study, we use the adapted cut-off and end-of-life recycling approaches as described by Hermansson et al. (2021). In these, the separation process needs to be allocated between the materials in the composite which is done using allocation factors $\alpha_{\_in}$ and $\alpha_{\_out}$. In this study, we chose to do this on a mass basis, and the allocation factors are found in Table S4.

Table S4: Allocation factors used in the allocation for lignin production when demand for lignin increases

Car mirror bracket	**Material**	$\alpha_{\_in}$	$\alpha_{\_out}$
GFRP	Polymer	n/a*	0.6
	Fiber	0.4	0.4
CFRP	Polymer	n/a*	0.8
	Fiber	0.2	0.2

* As only primary polymers were used in the production, no separation process was needed

3. Fuel reductions from lightweighting

3.1 Fuel reductions from lightweighting in an ICE-vehicle

Lowering the mass of the vehicle by substituting the exterior mirror brackets produced from GFRP with car mirror brackets produced from CFRP will lead to a lower fuel consumption in the use phase of the vehicle. The change in fuel consumption due to lightweighting (to be attributed to the CFRP mirror brackets as credits) is calculated using Equation S2 as suggested by Del Pero et al. (2017).

$$\Delta FC = \Delta m * FRV * 0.01 \qquad \text{(Eq. S2)}$$

Where *FC=fuel consumption (l/100 km)*, Δm*=vehicle mass reduction* and *FRV=fuel reduction value coefficient (l/100 km*100 kg)*. Note that the FRV is for decreasing the weight by 100 kg so the resulting fuel savings should be seen as an approximation.

The fuel reduction of the car mirror bracket throughout its lifetime is then by normalizing the value to per km by dividing Equation S2 by 100 and multiplying by the distance driven throughout the lifetime as shown in Equation S3:

$$FC\ (l/life\ time) = (\Delta FC * distance\ driven\ in\ km\ )/100 \qquad \text{(Eq. S3)}$$

The mass, *m*, of the different components (corresponds to two exterior mirror brackets) are:

- CFRP=190 grams=0.19 kg
- GFRP=240 grams=0.24 kg

Distance driven= 100 000 km and *FRV*=0.184 (liters/100 km*100 kg)[1]

This means that the fuel savings for each component are calculated using Equation S4:

$$FC = \frac{\Delta m * FRV * distance\ driven * 0.01}{100} = \frac{(0.24 - 0.19)kg * 0.184 * 0.01 * 100\ 000 km}{100} = 0.092\ liter \qquad \text{(Eq. S4)}$$

This means that the transition to the lighter car mirror brackets saves 0.092 liters of gasoline over 100 000 km.

[1] Average value for the arithmetic means for the PMR FRV for the different driving cycles for D-class vehicles as presented in Table III in the Supplementary material provided by Del Pero et al. (2017)

As we are only interested in the flows related to the car mirror brackets and not the entire car[2], the dataset "transport, passenger car, medium size, petrol EURO 5 (RER)" found in Ecoinvent 3.3 (Wernet et al., 2016) was modified. The dataset was modified to include the input of petroleum and the output of exhaust emissions as reported in Table 4 in Simons (2016), which is for medium size cars (vehicle weight 1600 kg). All other flows were removed from the dataset.

To be able to use the dataset, the decreased fuel consumption from lightweighting had to be recalculated into km using Equation S5. The density of 1 liter of petroleum is assumed to be 0.748 kg/liter[3] and the fuel use per km is 0.0592 kg/km (the latter value is from the Ecoinvent APOS 3.3 database):

$$\frac{fuel\ savings\ (liter) * kg\ gasoline\ per\ liter}{kg\ gasoline\ per\ km} = x\ km \qquad \text{(Eq. S5)}$$

The fuel savings is 0.092 liters which corresponds to 1.16 km of transportation as calculated using Equation S6.

$$\frac{0.092 * 0.748}{0.0592} = 1.16\ km \qquad \text{(Eq. S6)}$$

This means that -1.16 km of the adjusted version of the Ecoinvent APOS 3.3 process "transport, passenger car, medium size, petrol EURO 5 (RER)" was used as an input for the CFRP car mirror brackets put in a vehicle with ICE.

[2] We assume no power train adaption nor changes in battery size due to lightweighting

[3] The average value for gasoline density as reported by The Engineering Toolbox (2021)

3.2 Fuel reductions by lightweighting in an electric vehicle

The lightweighting of electric vehicles is calculated using the same rationale as for ICE-vehicles, however using a different fuel reduction value, called energy reduction value. In this paper we assume an energy reduction value (ERV) of 0.069 Wh/kg/km (Forell, Busa and Wilbert as cited in Johannisson et al. (2019)). The total energy reduction is then calculated by using Equation S7

$$EC = \Delta m * ERV * distance\ driven = (0.24kg - 0.19kg) * \frac{0.069Wh}{kg*km} * 100\,000\ km = 345\ Wh = 0.345\ kWh \quad \text{(Eq. S7)}$$

This means that -0.345 kWh of electricity (in this study assumed to be low voltage electricity generated in Germany in Ecoinvent APOS 3.3 as provided by Wernet et al. (2016)) was used as an input for the CFRP mirror brackets put in a BEV.

4. Inventory

Table S5: Inventory for the Organosolv lignin production, based on data found in Moncada et al. (2018).

Flow	Amount	Unit	Provider
Inputs			
Cooling energy	998	TJ	cooling energy, from natural gas, at cogen unit with absorption chiller 100kW | cooling energy | APOS, U - CH
Electricity	13	TJ	market for electricity, low voltage | electricity, low voltage | APOS, U - DE
Ethanol	10000	kg	market for ethanol, without water, in 99.7% solution state, from fermentation, at service station | ethanol, without water, in 99.7% solution state, from fermentation, at service station | APOS, U - RoW
Heat	1375	TJ	steam production in chemical industry | heat, in chemical industry | APOS, U - RER
Sulfuric acid	6000000	kg	sulfuric acid production | sulfuric acid | APOS, U - RER
Water	$4.231*10^9$	kg	market for tap water | tap water | APOS, U - Europe without Switzerland
Wood chips	$1.111*10^9$	kg	softwood forestry, spruce, sustainable forest management | wood chips, wet, measured as dry mass | APOS, U - DE
Outputs			
Carbon dioxide (assumed to be biogenic)	1000000	kg	n/a
Furfural	$1.2*10^7$	kg	n/a
Hemicellulosic sugars	$9.5*10^8$	kg	n/a
Hexose	$3.59*10^8$	kg	n/a
Non-hazardous waste - unspecified treatment	$8.57*10^8$	kg	n/a
Organosolv lignin	$1.91*10^8$	kg	n/a
Wastewater from hard fiberboard production	$2.989*10^9$	m3	n/a

Table S6: Inventory for the bio-based polyol production, based on data found in Fridrihsone-Girone (2015).

Flow	Amount	Unit	Provider
Inputs			
Electricity	75.6	MJ	market for electricity, low voltage | electricity, low voltage | APOS, U - DE
Heat	1681	MJ	market for heat, in chemical industry | heat, in chemical industry | APOS, U - RER
Rape seed	1878	kg	rape seed production | rape seed | APOS, U - DE
Triethanolamine	992	kg	ethanolamine production | triethanolamine | APOS, U - RER
Outputs			
Biobased polyol	2800	kg	n/a

The biobased polyols then replaced conventional polyols in a modified version of the dataset for "polyurethane production, ridgid foam | polyurethane, ridgid foam | APOS, U – RER" in Ecoinvent APOS 3.3 (Wernet et al., 2016) where flows related to Pentane and waste polyurethane also were removed.

Table S7: Inventory for the nitrogen production

Flow	Amount	Unit	Provider
Inputs			
Activated carbon	10	kg	activated carbon production, granular from hard coal | activated carbon, granular | APOS, U - RER
Compressed air	151312	m^3	compressed air production, 600 kPa gauge, >30kW, average generation | compressed air, 600 kPa gauge | APOS, U - RER
Output			
Nitrogen	700000	m^3	n/a

Table S8: Inputs for the GFRP mirror bracket

	Input	Amount	Unit	Provider
GFRP manufacturing	Glass fiber	0.096	kg	glass fibre production | glass fibre | APOS, U - RER
	Polyamide	0.144	kg	nylon 6-6 production | nylon 6-6 | APOS, U - RER
	Injection molding	0.24	kg	injection moulding | injection moulding | APOS, U - RER
End-of-life treatment	Waste plastic, mixture	-0.24	kg	treatment of waste plastic, mixture, sanitary landfill | waste plastic, mixture | APOS, U - Europe without Switzerland

When GFRP was recycled it was assumed that the process required 30 MJ/ kg composite (Witik et al., 2013) and used electricity as an energy carrier (Dong et al., 2018). We used the provider “market for electricity, low voltage | electricity, low voltage | APOS, U – DE” to model the electricity. It was assumed that the process recovered kg 0.048 glass fibers and 0.144 kg oil, represented by the process “market for petroleum | petroleum | APOS, U - GLO”.

Table S9: Inputs for the CFRP mirror bracket

	Input	Amount	Unit	Provider
CFRP manufacturing	Carbon fiber	0.038	kg	n/a
	Polyamide	0.152	kg	nylon 6-6 production | nylon 6-6 | APOS, U - RER
	Injection molding	0.19	kg	injection moulding | injection moulding | APOS, U - RER
Use phase	Transport, passenger car, medium size, petrol, Euro 5*	-1.16	km	transport, passenger car, medium size, petrol, EURO 5 | transport, passenger car, medium size, petrol, EURO 5 | APOS, U*
End-of-life treatment	Waste plastic, mixture	-0.19	kg	treatment of waste plastic, mixture, sanitary landfill | waste plastic, mixture | APOS, U - Europe without Switzerland

*Adapted for lightweighting, see Section 3.1

The inventory for the carbon fiber production was collected within the LIBRE (2016) project and is confidential, which is why it is not included.

When CFRP was recycled it was assumed that the process required 30 MJ/ kg composite (Witik et al., 2013) and used electricity as an energy carrier (Dong et al., 2018). We used the provider “market for electricity, low voltage | electricity, low voltage | APOS, U – DE” to model the electricity., it was assumed that the process recovered 0.03116 kg carbon fibers and 0.152 kg oil, represented by the process “market for petroleum | petroleum | APOS, U – GLO”.

5. Changing the energy system

When changing the energy background system from fossil-carbon rich to fossil-carbon lean energy mix, the energy mix of Sweden today was used as an approximation. This meant that the data for electricity use and energy use (such as heat and power) were changed throughout the system to mimic a Swedish energy system. This includes changing the electricity supply to Swedish, when possible, but also that heat and power providers are substituted to a corresponding Swedish provider. When no Swedish provider was available for the heat and/or power flow in the original process, the heat and power use was approximated by the energy mix used by the pulping industry in Sweden based on data from The Swedish Energy Agency (2017)) approximated of 28% electricity using the process "market for electricity, low voltage | electricity, low voltage | APOS, U – SE" and 72% heat and power co-generation from biomass using the process "heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | heat, district or industrial, other than natural gas | APOS, U – SE". In addition to this, when a process had a Swedish provider for other processes than energy inputs (such as material production), the processes were updated to use this one. If no Swedish provider was available, the provider was changed to a European average or equivalent[4]. If no appropriate fossil-carbon lean alternative was found, the process was left as is.

Efforts were made to change the energy sources throughout the system but could unfortunately not be done in a consistent way due to difference in data providers and time limitations. Changes were not made to processes considered to have a small influence on the overall impacts. The overall adaptations in the background systems that were done and could not be done are described below in relation to each material below:

[4] For ethanol production in the Organosolv process only Switzerland or rest-of-the world was available, so in this case Switzerland was chosen as a fossil-carbon lean alternative.

Processes applicable to all cases
Changes in energy supply were made to all included processes except for:

- Any facilities included in the data sets
- Any water used in the processes
- Any liquid fuels used in any type of vehicles, including fork lifters
- More upstream than for the landfilling
- Processes upstream from the injection molding process.
- Petroleum used as a credit for polymer after pyrolysis

CFRPs with bio-based carbon fibers
Changes in energy supply were made to all included processes except for:

- Bio-polyurethane production
    - The ethylene oxide and ammonia used for triethanolamine production or for the rape seeds, both used in the bio-based polyol production as this was deemed to be negligible to the overall impact.
- Organosolv lignin production
    - Anything more upstream than the sulfuric acid production or the cooling energy for the Organosolv pulping process
- Fiber production
    - Electrolytes used in precursor fiber spinning as this was deemed unnecessary and negligible.
    - Processes upstream the compression air production and activated carbon production for the nitrogen used in the carbonization and stabilization process.

CFRP with PAN-based fibers
Changes in energy supply were made to all included processes except for:

- Carbon fiber production
    - Processes more upstream than for the compression air production and activated carbon production for the nitrogen production in the carbonization and stabilization process.

GFRP

Changes in energy supply were not made to:

- Fiber production
    - Processes upstream in the glass fiber production process.

Systems processes

The following processes were systems processes and consists only of elementary flows:

- The methylene diphenyl diisocyanate (MDDI) (used in the bio-PU production)
- The polyacrylonitrile (PAN) fiber production (fossil carbon fiber precursor)
- The polyethylene (PE) production (used in bio-based precursor fiber spinning)
- The polypropylene (PP) production (used in bio-based precursor fiber spinning)
- The polyamide (PA) production (composite polymer matrix)

As these processes are systems processes and not unit processes (meaning that they only include elementary flows, i.e., aggregated LCI results), the providers could not be changed. Instead, flows related to fossil energy were removed and substituted with a fossil-carbon lean energy mix. This meant that inputs of hard coal, brown coal, and natural gas were removed. Oil was kept as it was considered to be primarily a raw material rather than energy source. The flows were then replaced with the corresponding energy used for the pulping industry in Sweden as earlier described in this section. In addition to this fossil emissions of carbon dioxide, carbon monoxide, and methane were removed from the outputs. Note that this is a simplification, and that in reality a share of the oil would be also used as fuel and not only raw materials. In addition to this, this approximation does not consider peat, which is assumed to have a very little influence on the end-results.

When calculating the input of energy being substituted, it was assumed that the natural gas had an energy content of 40.34 MJ/m^3 (Engineering Toolbox, 2008), and that the brown coal had an energy content of 11.9 MJ/kg, the hard coal 26.3 MJ/kg, which are the values used in the PAN-dataset in the ELCD database (Fazio & Pennington, 2005) and European Platform on Life Cycle Assessment (2018).

6. Sensitivity analysis

In this section, the details of the sensitivity analysis are included. The relative change has been calculated using Equation S8.

$$\frac{New\ Impact - Base\ case\ impact}{Base\ case\ impact} = Relative\ change\ in\ \% \qquad \text{(Eq. S8)}$$

6.1 Varying recycling rates

Table S10: Recycling rates when recycling rates are decreased with 10%

	Glass fibers	Carbon fibers	Polymer
R_1	0.4	0.72	0
R_2	0.9	0.9	0.9

Table S11: Recycling rates when recycling rates are increased with 10%

	Glass fibers	Carbon fibers	Polymer
R_1	0.6	0.92	0
R_2	1	1	1

Table S12: Relative change when varying the recycling rates

	Increase in recycling rate with 10%				Decrease in recycling rate with 10%			
	Cut-off approach		**EoL recycling approach**		**Cut-off approach**		**EoL recycling approach**	
Relative change	**GFRP**	**CFRP**	**GFRP**	**CFRP**	**GFRP**	**CFRP**	**GFRP**	**CFRP**
Climate impact	2%	-4%	0%	0%	-2%	5%	-4%	-1%
Energy use	2%	-5%	0%	0%	-2%	5%	-3%	1%
Resource use	-6%	-6%	0%	0%	6%	6%	-1%	-2%

6.2 Varying the quality of recycled fibers

The quality of the recovered glass fibers was assessed for a tensile strength reduction of 40% and 60%. The quality of the recovered carbon fibers was assessed for a tensile strength reduction of 28% and 8%.

Table S13: Relative change when varying the quality of the recovered fibers

	Increase in quality with 10%		Decrease in quality with 10%	
Relative change	**GFRP**	**CFRP**	**GFRP**	**CFRP**
Climate impact	-1%	-4%	1%	4%
Energy use	-1%	-5%	1%	5%
Resource use	-6%	-5%	6%	5%

6.3 Varying the energy consumption in pyrolysis

Table S14: Relative change when varying the energy consumption during pyrolysis

	Increase in energy consumption with 50% (45 MJ/kg)				Decrease in energy consumption with 50% (15 MJ/kg)			
	Cut-off approach		**EoL recycling approach**		**Cut-off approach**		**EoL recycling approach**	
Relative change	**GFRP**	**CFRP**	**GFRP**	**CFRP**	**GFRP**	**CFRP**	**GFRP**	**CFRP**
Climate impact	7%	6%	23%	22%	-7%	-6%	-23%	-22%
Energy use	7%	5%	27%	26%	-7%	-5%	-27%	-26%
Resource use	8%	13%	27%	40%	-8%	-13%	-27%	-40%

6.4 Varying energy consumption when using microwave heating

A reduction in energy consumption of 99% and 0% when transitioning from using microwave heating instead of furnaces when producing carbon fibers was assessed.

Table S15: Relative change when varying the energy consumption for the microwave heating of the carbon fibers

	0% decrease in energy consumption	**99% decrease in energy consumption**
Relative change	**CFRP**	**CFRP**
Climate impact	18%	-1%
Energy use	17%	-1%
Resource use	45%	-3%

6.5 Further mass reduction

Further design development could make the CFRP car mirror bracket even lighter. If the material composition stays constant (20% fibers and 80% PA), a mass reduction of 10% would result in a car mirror bracket weighting 0.171 kg. Using Equations S3 and S5, this leads to approximately 0.13 liters, corresponding to 1.60 km of fuel consumption being avoided. The influence the mass of the CFRP car mirror bracket has on the results is shown in Table S16.

Table S16: Relative change due to further lightweighting of CFRP car mirror bracket

	Relative change
Climate impact	-18%
Energy use	-15%
Resource use	-17%

7. Causual loop diagram

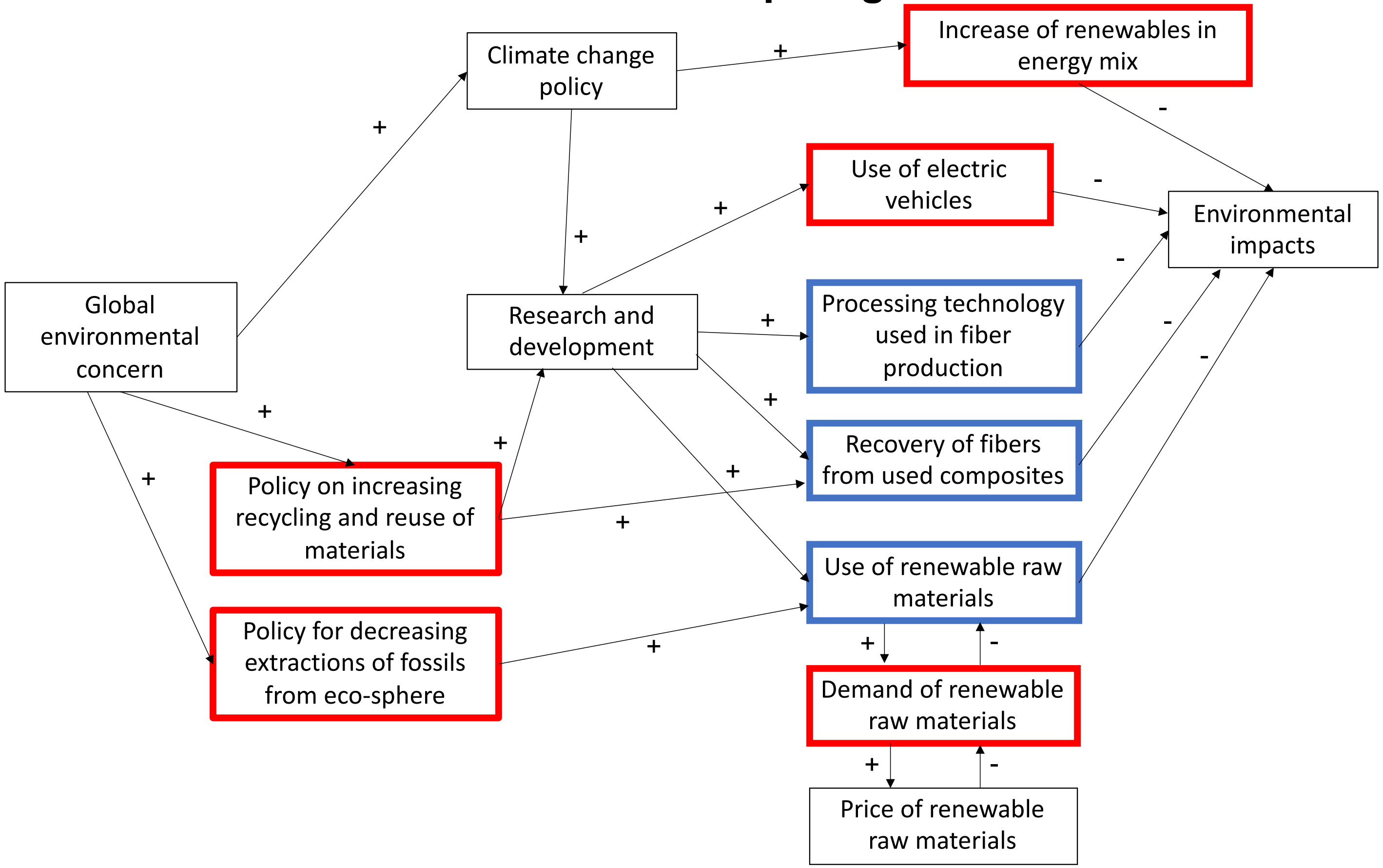

Figure S1: The causal loop diagram used for identifying interrelationships between the parameters. The red boxes illustrate parameters part of the background system and the blue boxes parameters part of the foreground system.

8. Identified parameters and subscenarios

Table S17: Parameters and sub-scenarios

	Parameter	Sub-scenario 1	Sub-scenario 2
Foreground system	Raw material input for fiber production	The raw material input for fiber production is based on fossil materials	Use of bio-based raw materials in fiber production
	Novel technology development	The carbon fibers are produced by means of furnaces	The carbon fibers are produced by means of microwave technology
	Composite waste management	Composites are sent to landfill and there is no recovery of materials at the end of life	Materials are recovered from the composites after use by means of pyrolysis
Background system	Fuel in use phase	Composites are used in a vehicle with an ICE[1]	Composites are used in a BEV[2]
	Demand for bio-based raw materials	The demand for lignin is low and thus also its price compared to other co-products	A greater demand for lignin increases its price significantly
	Environmental legislation	Legislation to reduce extraction of fossils from the eco-sphere	Legislation to promote recycling of materials after use
	Production electricity input	The energy mix has a high content of fossil carbon	The energy mix has transitioned to having low carbon content

[1]Internal combustion engine

[2]Battery electric vehicle

9. Cross consistency check for scenario development

Table S18: The cross-consistency check done in the scenario development, where 0 represents no correlation, 1 represents some correlation, and 2 represents a strong correlation

	Parameter 1, subsc. 1 No use of bio-raw material	Parameter 1, subsc. 2 Use of bio-raw material	Parameter 2, subsc. 1 Demand for bio-raw material is low	Parameter 2, subsc. 2 Demand for bio-raw material increases	Parameter 3, subsc. 1 No use of microwave tech.	Parameter 3, subsc. 2 Use of microwave tech.	Parameter 4, subsc. 1 No recycling of CF	Parameter 4, subsc. 2 Recycling of CF	Parameter 5, subsc. 1 Policy for decreasing the extraction of fossils from the eco-sphere	Parameter 5, subsc. 2 Policy for increasing recycling and reuse of materials	Parameter 6, subsc. 1 The energy mix has a high content of fossil-carbon	Parameter 6, subsc. 2 Fossil-carbon lean energy mix
Parameter 1, subsc. 1 No use of bio-raw material												
Parameter 1, subsc. 2 Use of bio-raw material												
Parameter 2, subsc. 1 Demand for bio-raw material is low	2	0										
Parameter 2, subsc. 1 Demand for bio-raw material increases	0	2										
Parameter 3, subsc. 1 No use of microwave tech	1	1	1	0								
Parameter 3, subsc. 2 Use of microwave tech	0	2	0	2								
Parameter 4, subsc. 1 No recycling of CF	0	0	0	0	0	0						
Parameter 4, subsc. 2 Recycling of CF	1	1	0	0	0	0						
Parameter 5, subsc. 1 Policy for decreasing the extraction of fossils from the eco-sphere	1	2	0	2	1	2	1	2				
Parameter 5, subsc. 2 Policy for increasing recycling and reuse of materials	2	1	0	0	0	0	0	2				
Parameter 6, subsc. 1 The energy mix has a high content of fossil-carbon	1	0	1	1	1	0	1	0	0	1		
Parameter 6, subsc. 2 Fossil-carbon lean energy mix	0	2	0	2	0	1	0	1	2	1		
Parameter 7, subsc. 1 ICE cars	1	0	1	0	1	0	1	0	0	1	2	0
Parameter 7, subsc. 2 BEVs	0	2	0	2	0	1	0	1	2	1	0	2

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