

Supplementary Materials Table S1: Detailed description of parameters and future projections used for the case study

	Key factor	Projection	Description	Implementation and data basis	Data details
	1.1 Hot forming process	A	Business as usual projection: No substantial process changes. Improvements only through continuous improvement.	This projection is implemented by changing the energy consumption of the hot forming process in the foreground database with Wurst. The energy consumption of all forms of energy is reduced linearly with 1% reduction per year as a conservative assumption.	Consumption data from industrial processes are used as baseline values. These values cannot be published for reasons of confidentiality.
		B	Moderate electrification projection: Natural gas consuming heating processes are gradually electrified starting in 2030 reaching 100% electrification by 2050. Energy efficiency measures from projection A also apply.	This projection is implemented by changing the energy consumption of the hot forming process in the foreground database with Wurst. Starting in 2030 the consumption of natural gas is reduced linearly reaching zero in 2050. At the same time the consumption of electricity is increased. As a simple assumption 1 kWh of natural gas is compensated by 1 kWh of electricity. Furthermore, the changes from projection A apply.	
		C	Moderate usage of hydrogen projection: Natural gas in heating processes is gradually substituted by hydrogen starting in 2030 reaching 100% hydrogen usage by 2050. Energy efficiency measures from projection A also apply.	This projection is implemented by changing the energy consumption of the hot forming process in the foreground database with Wurst. Starting in 2030 the consumption of natural gas is reduced linearly reaching zero in 2050. At the same time hydrogen is integrated as a new form of energy and the consumption of hydrogen is increased. As a simple assumption 1 kWh of natural gas is compensated by 1 kWh of hydrogen. Furthermore, the changes from projection A apply.	
		D	Fast electrification projection: Heating processes are electrified immediately reaching 100% electrification by 2030. Energy efficiency measures from projection A also apply.	This projection is implemented by changing the energy consumption of the hot forming process in the foreground database with Wurst. Starting in 2020 the consumption of natural gas is reduced linearly reaching zero in 2030. At the same time the consumption of electricity is increased. As a simple assumption 1 kWh of natural gas is compensated by 1 kWh of electricity. Furthermore, the changes from projection A apply.	
		E	Worst case projection: No further process improvement and no changes in energy consumption.	No changes of the hot forming process in the foreground database.	
	1.2 Coating (cathodic dip coating)	A	Business as usual projection: No substantial process changes. Improvements only through continuous improvement.	This projection is implemented by changing the energy consumption of the coating process in the foreground database with Wurst. The energy consumption of all forms of energy is reduced linearly with 1% reduction per year as a conservative assumption.	
		B	Moderate electrification projection: Natural gas consuming heating processes are gradually electrified starting in 2030 reaching 100% electrification by 2050. Energy efficiency measures from projection A also apply.	This projection is implemented by changing the energy consumption of the coating process in the foreground database with Wurst. Starting in 2030 the consumption of natural gas is reduced linearly reaching zero in 2050. At the same time the consumption of electricity is increased. As a simple assumption 1 kWh of natural gas is compensated by 1 kWh of electricity. Furthermore, the changes from projection A apply.	
		C	Moderate usage of hydrogen projection: Natural gas in heating processes is gradually substituted by hydrogen starting in 2030 reaching 100% hydrogen usage by 2050. Energy efficiency measures from projection A also apply.	This projection is implemented by changing the energy consumption of the coating process in the foreground database with Wurst. Starting in 2030 the consumption of natural gas is reduced linearly reaching zero in 2050. At the same time hydrogen is integrated as a new form of energy and the consumption of hydrogen is increased. As a simple assumption 1 kWh of natural gas is compensated by 1 kWh of hydrogen. Furthermore, the changes from projection A apply.	
		D	Fast electrification projection: Heating processes are electrified immediately reaching 100% electrification by 2030. Energy efficiency measures from projection A also apply.	This projection is implemented by changing the energy consumption of the coating process in the foreground database with Wurst. Starting in 2020 the consumption of natural gas is reduced linearly reaching zero in 2030. At the same time the consumption of electricity is increased. As a simple assumption 1 kWh of natural gas is compensated by 1 kWh of electricity. Furthermore, the changes from projection A apply.	
		E	Worst case projection: No further process improvement and no changes in energy consumption.	No changes of the coating process in the foreground database.	

Foreground	1.3 Aluminium Casting and Extrusion	A	Business as usual projection: No substantial process changes. Improvements only through continuous improvement.	This projection is implemented by changing the energy consumption of the aluminium casting and extrusion process in the foreground database with Wurst. The energy consumption of all forms of energy is reduced linearly with 1% reduction per year as a conservative assumption.
		B	Moderate electrification projection: Natural gas consuming heating processes are gradually electrified starting in 2030 reaching 100% electrification by 2050. Energy efficiency measures from projection A also apply.	This projection is implemented by changing the energy consumption of the aluminium casting and extrusion process in the foreground database with Wurst. Starting in 2030 the consumption of natural gas is reduced linearly reaching zero in 2050. At the same time the consumption of electricity is increased. As a simple assumption 1 kWh of natural gas is compensated by 1 kWh of electricity. Furthermore, the changes from projection A apply.
		C	Moderate usage of hydrogen projection: Natural gas in heating processes is gradually substituted by hydrogen starting in 2030 reaching 100% hydrogen usage by 2050. Energy efficiency measures from projection A also apply.	This projection is implemented by changing the energy consumption of the aluminium casting and extrusion process in the foreground database with Wurst. Starting in 2030 the consumption of natural gas is reduced linearly reaching zero in 2050. At the same time hydrogen is integrated as a new form of energy and the consumption of hydrogen is increased. As a simple assumption 1 kWh of natural gas is compensated by 1 kWh of hydrogen. Furthermore, the changes from projection A apply.
		D	Fast electrification projection: Heating processes are electrified immediately reaching 100% electrification by 2030. Energy efficiency measures from projection A also apply.	This projection is implemented by changing the energy consumption of the aluminium casting and extrusion process in the foreground database with Wurst. Starting in 2020 the consumption of natural gas is reduced linearly reaching zero in 2030. At the same time the consumption of electricity is increased. As a simple assumption 1 kWh of natural gas is compensated by 1 kWh of electricity. Furthermore, the changes from projection A apply.
		E	Worst case projection: No further process improvement and no changes in energy consumption.	No changes of the aluminium casting and extrusion process in the foreground database.
	1.4 Other processes: Welding, Surface Treatment, Forming and Machining	A	Business as usual projection: No substantial process changes. Improvements only through continuous improvement.	This projection is implemented by changing the energy consumption of the aluminium casting and extrusion process in the foreground database with Wurst. The energy consumption of all forms of energy is reduced linearly with 1% reduction per year as a conservative assumption.
		B	Moderate electrification projection: Natural gas consuming heating processes are gradually electrified starting in 2030 reaching 100% electrification by 2050. Energy efficiency measures from projection A also apply.	This projection is implemented by changing the energy consumption of the aluminium casting and extrusion process in the foreground database with Wurst. Starting in 2030 the consumption of natural gas is reduced linearly reaching zero in 2050. At the same time the consumption of electricity is increased. As a simple assumption 1 kWh of natural gas is compensated by 1 kWh of electricity. Furthermore, the changes from projection A apply.
		C	Worst case projection: No further process improvement and no changes in energy consumption.	No changes of the aluminium casting and extrusion process in the foreground database.

Consumption data from industrial processes are used as baseline values These values cannot be published for reasons of confidentiality.

	1.5 Hybrid forming and curing process	A	Business as usual projection: No substantial process changes. Improvements only through continuous improvement.	This projection is implemented by changing the energy consumption of the hybrid forming and curing process in the foreground database with Wurst. The baseline value is based on measurements. The energy consumption of all forms of energy is reduced linearly with 1% reduction per year as a conservative assumption.
		B	Matrix material projection: A fast-curing matrix material is used to reduce the curing time and consequently the energy consumption. From 2030, the curing time can be reduced to three minutes. Energy efficiency measures from projection A also apply.	This projection is implemented by changing the energy consumption of the hybrid forming and curing process in the foreground database with Wurst. In 2030, a technology change to a matrix material with a curing time of three minutes is carried out. This value is based on manufacturers' specifications for prepreg materials, such as the Hexcel Corporation [72]. Furthermore, the changes from projection A apply.
		C	Matrix material and energy efficiency projection: In addition to the usage of a fast-curing matrix material, the energy consumption can be reduced by further 50% until 2050.	This projection is implemented by changing the energy consumption of the hybrid forming and curing process in the foreground database with Wurst. From 2020 and in addition to the technology change to a fast-curing matrix material from projection B, a linear reduction of the energy consumption by 50% until 2050 is assumed. According to expert interviews, this can be achieved by using more efficient press technologies and mould heating approaches.
		D	Worst case projection: No further process improvement and no changes in energy consumption.	No changes of the hybrid forming and curing process in the foreground database.
	1.6 Prepreg production and cutting	A	Business as usual projection: No substantial process changes. Improvements only through continuous improvement.	This projection is implemented by changing the energy consumption of the prepreg production and cutting process in the foreground database with Wurst. The process includes fibre fabric, thermoset prepreg production and its cutting, with their baseline energy consumptions based on [64-67]. From 2020 the energy consumption of all forms of energy is reduced linearly with 1% reduction per year as a conservative assumption.
		B	Energy efficiency projection: Storage, climate control, production and processing steps of thermoset CFRP prepreps are optimised so that the energy consumption can be reduced by 50% until 2050.	This projection is implemented by changing the energy consumption of the prepreg production and cutting process in the foreground database with Wurst. From 2020 the energy consumption is reduced linearly reaching 50% until 2050. The value is based on information of process experts.
		C	Worst case projection: No further process improvement and no changes in energy consumption.	No changes of the prepreg production and cutting process in the foreground database.

Consumption data from industrial processes are used as baseline values These values cannot be published for reasons of confidentiality.

1.7 Material efficiency in production processes	A	Moderate improvement of material efficiency: Half of the theoretical potential for increasing material efficiency from projection B is achieved.	This projection is implemented by changing the amount of needed material for each design variant in the foreground database with Wurst. It is assumed that only half of the improvements described in projection B will be achieved until 2050.	Material yield data from industrial processes are used as baseline values. These values cannot be published for reasons of confidentiality.
	B	Substantial improvement of material efficiency: Material efficiency is increased according to theoretical potentials.	This projection is implemented by changing the amount of needed material for each design variant in the foreground database with Wurst. The amount is reduced linearly starting in 2020 and reaching the full theoretical potential in 2050. Different values for theoretically possible material efficiency are defined for the different materials: Steel: In the sustainable development scenario of IEA it is projected that the total consumption of steel can be reduced by around 13% due to increased yields in manufacturing processes through optimizations in the manufacturing [27]. Aluminium: The authors assume a possible improvement in material yield of 10 percentage points for the aluminium extrusion production. This coincides well with the data from Global Aluminium Cycle 2021 [73] where the generation of new scrap during production is reduced from 39.7% to 29.2% from 2022 to 2050 under the 2022 IAI Reference Scenario. However, the effect on the GWP is comparatively small, as the material from extrusion is directly reused for the casting process in the process modeling used. Prepreg: For prepreg material offcuts, it is assumed that these can be reduced from 8% to 4% by 2050. This assumption is based on the information provided by Hohmann [15]. Precursor: For the conversion of PAN precursor to carbon fibres, it is assumed that the material yield can be increased linearly from 50% to 60% by 2050. This increase in material efficiency is based on literature data [15,17,74].	
	C	Worst case projection: No changes of material efficiency	No changes of the material consumption in the foreground database.	

2.1 Steel production	A	Stated policies projection: The GWP of steel coil production does not change significantly between 2020 and 2050. Only a minor recution of 21% until 2050 is considered (direct emissions).	This projection is implemented by changing the GWP per kg steel coil in the background database with Wurst based on the International Energy Agency (IEA) "Stated Policies Scenario" (STEPS) [27]. In this scenario the direct emission intensity of steel is reduced caused by a higher share of secondary steel production with a reduced emission intensity and the increased use of the natural gas based DRI-EAF steel making process. The coal based BF-BOF steel making process remains the most important technology. The scenario delivers only global average data that were used in this study. As the IEA scenario (scenario for crude steel production) does not consider upstream emissions from iron ore mining and downstream emissions from finishing processes (e.g. rolling), these emissions are added to the IEA scenario data. For the iron ore mining a constant value of roughly 0,14 kg CO2 eq. per kg steel based on historical data shown in Wang et al. [75] is considered. To account for emissions from finishing processes, a constant finishing factor is calculated based on the base year emissions from the Worldsteel "finished cold rolled coil" dataset [60] and the IEA baseyear emissions.	<table><thead><tr><th>Year</th><th>Baseline (Worldsteel)</th><th>Iron ore mining</th><th>Finishing factor</th><th>Scenario data (IEA)</th></tr></thead><tbody><tr><td>2020</td><td>2.38</td><td>0.14</td><td>0.00</td><td>2.38</td></tr><tr><td>2030</td><td>2.20</td><td>0.14</td><td>0.00</td><td>2.20</td></tr><tr><td>2040</td><td>2.01</td><td>0.14</td><td>0.00</td><td>2.01</td></tr><tr><td>2050</td><td>1.89</td><td>0.14</td><td>0.00</td><td>1.89</td></tr></tbody></table>	Year	Baseline (Worldsteel)	Iron ore mining	Finishing factor	Scenario data (IEA)	2020	2.38	0.14	0.00	2.38	2030	2.20	0.14	0.00	2.20	2040	2.01	0.14	0.00	2.01	2050	1.89	0.14	0.00	1.89				
	Year	Baseline (Worldsteel)	Iron ore mining	Finishing factor	Scenario data (IEA)																												
	2020	2.38	0.14	0.00	2.38																												
2030	2.20	0.14	0.00	2.20																													
2040	2.01	0.14	0.00	2.01																													
2050	1.89	0.14	0.00	1.89																													
B	Sustainable development projection: The GWP of steel coil production is reduced significantly between 2020 and 2050. A reduction of 61% until 2050 is achieved. The reduction is based on the introduction of new low emission production technologies.	This projection is implemented by changing the GWP per kg steel coil in the background database with Wurst based on the IEA "Sustainable Development Scenario" (SDS) [27]. This scenario includes faster changes and innovations in the steel sector to reach "net-zero" CO2 emissions (-90% compared to 2019) for the energy system as a whole by around 2070. This is achieved through the introduction of new steel making technologies with reduced emission intensities. Relevant technologies are the hydrogen based DRI-EAF steel making process and carbon capture technologies in combination with conventional steel making technologies. The scenario delivers only global average data that were used in this study. As the IEA scenario (scenario for crude steel production) does not consider upstream emissions from iron ore mining and downstream emissions from finishing processes (e.g. rolling), these emissions are added to the IEA scenario data. For the iron ore mining a constant value of roughly 0,14 kg CO2 eq. per kg steel based on historical data shown in Wang et al. [75] is considered. To account for emissions from finishing processes, a constant finishing factor is calculated based on the base year emissions from the Worldsteel "finished cold rolled coil" dataset for Europe [60] and the IEA baseyear emissions.	<table><thead><tr><th>Year</th><th>Baseline (Worldsteel)</th><th>Iron ore mining</th><th>Finishing factor</th><th>Scenario data (IEA)</th></tr></thead><tbody><tr><td>2020</td><td>2.38</td><td>0.14</td><td>0.00</td><td>2.38</td></tr><tr><td>2030</td><td>1.86</td><td>0.14</td><td>0.00</td><td>1.86</td></tr><tr><td>2040</td><td>1.37</td><td>0.14</td><td>0.00</td><td>1.37</td></tr><tr><td>2050</td><td>0.94</td><td>0.14</td><td>0.00</td><td>0.94</td></tr></tbody></table>	Year	Baseline (Worldsteel)	Iron ore mining	Finishing factor	Scenario data (IEA)	2020	2.38	0.14	0.00	2.38	2030	1.86	0.14	0.00	1.86	2040	1.37	0.14	0.00	1.37	2050	0.94	0.14	0.00	0.94					
Year	Baseline (Worldsteel)	Iron ore mining	Finishing factor	Scenario data (IEA)																													
2020	2.38	0.14	0.00	2.38																													
2030	1.86	0.14	0.00	1.86																													
2040	1.37	0.14	0.00	1.37																													
2050	0.94	0.14	0.00	0.94																													
C	Net Zero steel projection: The GWP of steel coil production is reduced significantly between 2020 and 2050 reaching a reduction of 89% until 2050. The reduction is based on the faster introduction of new low emission production technologies.	This projection is implemented by changing the GWP per kg steel coil in the background database with Wurst based on the Net-Zero Steel Project (NZS) scenario [76]. The Net-Zero Steel Project introduces decarbonization pathways that allow the decarbonization of the steel sector by 2050 by implementing higher shares of secondary steel production, hydrogen based DRI-EAF and CCUS technologies. The scenario data specific for the region Europe where used in this study. As the scenario (scenario for crude steel production) does not consider upstream emissions from iron ore mining and downstream emissions from finishing processes (e.g. rolling), these emissions are added to the scenarios emission data. For the iron ore mining a constant value of roughly 0,14 kg CO2 eq. per kg steel based on historical data shown in Wang et al. [75] is considered. To account for emissions from finishing processes, a constant finishing factor is calculated based on the base year emissions from the Worldsteel "finished cold rolled coil" dataset for Europe [60] and the IEA baseyear emissions. Furthermore, the NZS scenario does not include emissions from energy supply in their emission calculation. Therefore emissions from energy supply are calculated separately based on the energy needs given in the NZS scenario.	<table><thead><tr><th>Year</th><th>Baseline (Worldsteel)</th><th>Iron ore mining</th><th>Energy supply (NZ)</th><th>Finishing factor</th><th>Scenario data (NZ)</th></tr></thead><tbody><tr><td>2020</td><td>2.38</td><td>0.14</td><td>0.00</td><td>0.00</td><td>2.38</td></tr><tr><td>2030</td><td>2.20</td><td>0.14</td><td>0.00</td><td>0.00</td><td>2.20</td></tr><tr><td>2040</td><td>1.10</td><td>0.14</td><td>0.00</td><td>0.00</td><td>1.10</td></tr><tr><td>2050</td><td>0.27</td><td>0.14</td><td>0.00</td><td>0.00</td><td>0.27</td></tr></tbody></table>	Year	Baseline (Worldsteel)	Iron ore mining	Energy supply (NZ)	Finishing factor	Scenario data (NZ)	2020	2.38	0.14	0.00	0.00	2.38	2030	2.20	0.14	0.00	0.00	2.20	2040	1.10	0.14	0.00	0.00	1.10	2050	0.27	0.14	0.00	0.00	0.27
Year	Baseline (Worldsteel)	Iron ore mining	Energy supply (NZ)	Finishing factor	Scenario data (NZ)																												
2020	2.38	0.14	0.00	0.00	2.38																												
2030	2.20	0.14	0.00	0.00	2.20																												
2040	1.10	0.14	0.00	0.00	1.10																												
2050	0.27	0.14	0.00	0.00	0.27																												

2.2 Aluminum production (primary)	A	Baseline projection: The GWP of primary aluminum production in Europe does not change significantly between 2020 and 2050.	This projection is implemented by changing the GWP per kg primary aluminium in the background database with Wurst. As no business-as-usual (BAU) scenario was available for Europe, the percentage reductions assumed in the BAU scenario of the International Aluminium Institute (IAI) were applied [28]. This scenario assumes a 2% reduction in GWP per kg of primary aluminum production from 2018 to 2050.	<table><tr><th>Year</th><th>Baseline (EA)</th><th>BAU (IAI)</th></tr><tr><td>2020</td><td>6,7</td><td>6,7</td></tr><tr><td>2030</td><td>6,7</td><td>6,7</td></tr><tr><td>2040</td><td>6,6</td><td>6,6</td></tr><tr><td>2050</td><td>6,6</td><td>6,6</td></tr></table>	Year	Baseline (EA)	BAU (IAI)	2020	6,7	6,7	2030	6,7	6,7	2040	6,6	6,6	2050	6,6	6,6				
	Year	Baseline (EA)	BAU (IAI)																				
	2020	6,7	6,7																				
2030	6,7	6,7																					
2040	6,6	6,6																					
2050	6,6	6,6																					
B	Renewable energy projection: The GWP of primary aluminum production in Europe is reduced significantly between 2020 and 2050. The reductions are caused through the decarbonization of the power sector.	This projection is implemented by changing the GWP per kg primary aluminium in the background database with Wurst based on the European Aluminium (EA) Vision 2050 scenario without the breakthrough of technologies that reduce direct emissions of the aluminium smelting process [29]. As the EA scenario only considers emissions from the aluminium smelting process, further upstream emissions from mining, refining and anode production are calculated based on the Beyond 2°C aligned scenario from International Aluminium Institute (IAI) [28].	<table><tr><th>Year</th><th>Baseline (EA)</th><th>Upstream process (IAI)</th><th>Smelting (EA)</th></tr><tr><td>2020</td><td>6,7</td><td>0</td><td>0</td></tr><tr><td>2030</td><td>5,6</td><td>0</td><td>0</td></tr><tr><td>2040</td><td>4,0</td><td>0</td><td>0</td></tr><tr><td>2050</td><td>3,1</td><td>0</td><td>0</td></tr></table>	Year	Baseline (EA)	Upstream process (IAI)	Smelting (EA)	2020	6,7	0	0	2030	5,6	0	0	2040	4,0	0	0	2050	3,1	0	0
Year	Baseline (EA)	Upstream process (IAI)	Smelting (EA)																				
2020	6,7	0	0																				
2030	5,6	0	0																				
2040	4,0	0	0																				
2050	3,1	0	0																				
C	Renewable energy and technology breakthrough projection: The GWP of primary aluminium production in Europe is reduced significantly between 2020 and 2050. The reductions are caused through the decarbonization of the power sector and the introduction of smelting technologies that reduce direct emissions.	This projection is implemented by changing the GWP per kg primary aluminium in the background database with Wurst based on the European Aluminium (EA) Vision 2050 scenario with the breakthrough of technologies that reduce direct emissions of the aluminium smelting process [29]. The EA scenario considers a conservative introduction of carbon capture technologies and the introduction of inert anode technologies to reduce direct emissions. It is assumed that until 2050 23 percent of the European primary aluminium production will avoid direct emissions through these technologies. Furthermore, the introduction of incremental technology changes such as energy efficiency are considered. As the EA scenario only considers emissions from the aluminium smelting process, further upstream emissions from mining, refining and anode production are calculated based on the 1.5 degrees aligned scenario from International Aluminium Institute (IAI) [28].	<table><tr><th>Year</th><th>Baseline (EA)</th><th>Upstream process (IAI)</th><th>Smelting (EA)</th></tr><tr><td>2020</td><td>6,7</td><td>0</td><td>0</td></tr><tr><td>2030</td><td>5,0</td><td>0</td><td>0</td></tr><tr><td>2040</td><td>2,6</td><td>0</td><td>0</td></tr><tr><td>2050</td><td>1,6</td><td>0</td><td>0</td></tr></table>	Year	Baseline (EA)	Upstream process (IAI)	Smelting (EA)	2020	6,7	0	0	2030	5,0	0	0	2040	2,6	0	0	2050	1,6	0	0
Year	Baseline (EA)	Upstream process (IAI)	Smelting (EA)																				
2020	6,7	0	0																				
2030	5,0	0	0																				
2040	2,6	0	0																				
2050	1,6	0	0																				
2.3 Electricity generation (electricity used for production processes and use stage)	A	IAM Scenario SSP2 Baseline: The GWP of electricity generation in Europe does not change significantly between 2020 and 2050.	This projection is implemented by changing the background database ecoinvent by using Premise according to the integrated assessment mode (IAM) IMAGE. For the baseline projection the database is changed according to the SSP2 "Middle-of-the-Road" socio-economic pathway with a prospective scenario that complies with the climate change mitigation target RCP 6 corresponding to a global atmospheric temperature increase by 2100 with respect to pre-industrial levels of 3.5°C [46].	<table><tr><th>Year</th><th>Market group for electricity, high voltage, RER</th></tr><tr><td>2020</td><td>0,32</td></tr><tr><td>2030</td><td>0,29</td></tr><tr><td>2040</td><td>0,35</td></tr><tr><td>2050</td><td>0,52</td></tr></table>	Year	Market group for electricity, high voltage, RER	2020	0,32	2030	0,29	2040	0,35	2050	0,52									
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	2020	0,32																					
2030	0,29																						
2040	0,35																						
2050	0,52																						
B	IAM Scenario SSP2 Climate Policy: The GWP of electricity generation in Europe is reduced significantly between 2020 and 2050 through the expansion of renewable energy generation and the introduction of carbon capture technologies.	This projection is implemented by changing the background database ecoinvent by using Premise according to the integrated assessment mode (IAM) IMAGE. For the climate policy projection the database is changed according to the SSP2 "Middle-of-the-Road" socio-economic pathway with a prospective scenario that complies with the climate change mitigation target RCP 2.6 corresponding to a global atmospheric temperature increase by 2100 with respect to pre-industrial levels of below 2°C [46].	<table><tr><th>Year</th><th>Market group for electricity, high voltage, RER</th></tr><tr><td>2020</td><td>0,32</td></tr><tr><td>2030</td><td>0,24</td></tr><tr><td>2040</td><td>0,13</td></tr><tr><td>2050</td><td>-0,05</td></tr></table>	Year	Market group for electricity, high voltage, RER	2020	0,32	2030	0,24	2040	0,13	2050	-0,05										
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2040	0,13																						
2050	-0,05																						
C	IAM Scenario SSP2 Paris Agreement: The GWP of electricity generation in Europe is reduced significantly between 2020 and 2050 through the faster expansion of renewable energy generation and the introduction of carbon capture technologies.	This projection is implemented by changing the background database ecoinvent by using Premise according to the integrated assessment mode (IAM) IMAGE. For the Paris agreement projection the database is changed according to the SSP2 "Middle-of-the-Road" socio-economic pathway with a prospective scenario that complies with the climate change mitigation target RCP 1.9 corresponding to a global atmospheric temperature increase by 2100 with respect to pre-industrial levels of 1.5°C [46].	<table><tr><th>Year</th><th>Market group for electricity, high voltage, RER</th></tr><tr><td>2020</td><td>0,32</td></tr><tr><td>2030</td><td>0,07</td></tr><tr><td>2040</td><td>-0,01</td></tr><tr><td>2050</td><td>-0,07</td></tr></table>	Year	Market group for electricity, high voltage, RER	2020	0,32	2030	0,07	2040	-0,01	2050	-0,07										
Year	Market group for electricity, high voltage, RER																						
2020	0,32																						
2030	0,07																						
2040	-0,01																						
2050	-0,07																						

2.4 Epoxy production	A	Baseline projection: The GWP of epoxy resin production does not change significantly between 2020 and 2050. Only the energy-related emissions can be slightly reduced, e.g. through efficiency measures.	This projection is implemented by changing the GWP per kg epoxy resin in the background database with Wurst. Using the baseline value according to Bachmann et al. [62] and the share of energy-related emissions according to Hohmann and Frank [31], it is assumed that the energy-related emissions can be reduced by 1% per year until 2050.	<table><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr><tr><td>2020</td><td>8,10</td></tr><tr><td>2030</td><td>7,72</td></tr><tr><td>2040</td><td>7,38</td></tr><tr><td>2050</td><td>7,07</td></tr></table>	Year	GWP in kg CO ₂ eq. per kg	2020	8,10	2030	7,72	2040	7,38	2050	7,07
	Year	GWP in kg CO ₂ eq. per kg												
	2020	8,10												
	2030	7,72												
2040	7,38													
2050	7,07													
B	Renewable energy projection: The GWP of epoxy resin is reduced from 2030 by using renewable energy sources and power-to-X technologies (PtX). By 2050, a complete switch to renewable energy sources is achieved.	This projection is implemented by changing the GWP per kg epoxy in the background database with Wurst. Based on the data provided by Hohmann and Frank [31], the GWP of epoxy production can be reduced by up to 37% through the use of renewable energy sources and PtX technologies. It is assumed that this potential can be fully exploited by 2050. According to the information given by Hohmann [70], it is considered that the switch to PtX technologies will take place between 2030 and 2040.	<table><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr><tr><td>2020</td><td>8,10</td></tr><tr><td>2030</td><td>7,50</td></tr><tr><td>2040</td><td>5,70</td></tr><tr><td>2050</td><td>5,10</td></tr></table>	Year	GWP in kg CO ₂ eq. per kg	2020	8,10	2030	7,50	2040	5,70	2050	5,10	
Year	GWP in kg CO ₂ eq. per kg													
2020	8,10													
2030	7,50													
2040	5,70													
2050	5,10													
C	Biobased material projection: The GWP of epoxy resin is further reduced from 2030 by an increased technology integration of biobased raw materials in epoxy production. A complete switch to biobased raw materials is assumed by 2050. However, fossil fuels are still used in the production of raw materials and epoxy resin.	This projection is implemented by changing the GWP per kg epoxy in the background database with Wurst. Based on the data provided by Hohmann [70], the GWP of epoxy can be reduced by 48% by using biobased aniline as a feedstock of the epoxy resin. It is assumed that this potential can be fully exploited by 2050. As in projection B, it is considered that the switch to biobased raw materials will increasingly take place between 2030 and 2040.	<table><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr><tr><td>2020</td><td>8,10</td></tr><tr><td>2030</td><td>7,32</td></tr><tr><td>2040</td><td>4,99</td></tr><tr><td>2050</td><td>4,21</td></tr></table>	Year	GWP in kg CO ₂ eq. per kg	2020	8,10	2030	7,32	2040	4,99	2050	4,21	
Year	GWP in kg CO ₂ eq. per kg													
2020	8,10													
2030	7,32													
2040	4,99													
2050	4,21													
D	Renewable energy and biobased material projection: The combined use of renewable energy sources, PtX-technologies (projection B) and biobased raw materials (projection C) leads to a significant reduction in the GWP of epoxy resin by 2050.	This projection is implemented by changing the GWP per kg epoxy in the background database with Wurst. Based on the information provided by Hohmann [70], the combined use of renewable energy sources, PtX technologies and biobased raw materials in epoxy production results in a GWP reduction potential of 78%. It is assumed that this potential can be fully exploited by 2050, with the technologies being integrated mainly between 2030 and 2040.	<table><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr><tr><td>2020</td><td>8,10</td></tr><tr><td>2030</td><td>6,84</td></tr><tr><td>2040</td><td>3,05</td></tr><tr><td>2050</td><td>1,79</td></tr></table>	Year	GWP in kg CO ₂ eq. per kg	2020	8,10	2030	6,84	2040	3,05	2050	1,79	
Year	GWP in kg CO ₂ eq. per kg													
2020	8,10													
2030	6,84													
2040	3,05													
2050	1,79													

2.5 Precursor production	A	Baseline projection: The GWP of petroleum based polyacrylonitrile (PAN) fibres as raw material for carbon fibres does not change significantly between 2020 and 2050. Only the energy-related emissions can be slightly reduced, e.g. through efficiency measures.	This projection is implemented by changing the GWP per kg precursor material in the background database with Wurst. Polyacrylonitrile (PAN) is considered as a precursor material for carbon fibre production, as it is the most common used precursor according to Dér et al. [17]. Based on the data for PAN fibre production from Das [63], it is assumed that energy-related emissions can be reduced by 1% per year until 2050, e.g. through efficiency measures.	<table><thead><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr></thead><tbody><tr><td>2020</td><td>5.12</td></tr><tr><td>2030</td><td>5.00</td></tr><tr><td>2040</td><td>4.89</td></tr><tr><td>2050</td><td>4.79</td></tr></tbody></table>	Year	GWP in kg CO ₂ eq. per kg	2020	5.12	2030	5.00	2040	4.89	2050	4.79
	Year	GWP in kg CO ₂ eq. per kg												
	2020	5.12												
	2030	5.00												
	2040	4.89												
2050	4.79													
B	Renewable energy projection: The GWP of petroleum based PAN precursor is reduced from 2030 by using renewable energy sources and power-to-X technologies (PtX) in the precursor and its feedstocks production processes. By 2050, a complete switch to renewable energy sources is achieved.	This projection is implemented by changing the GWP per kg precursor material in the background database with Wurst. Based on the data for material and energy flows in PAN fibre production according to Das [63], it is assumed that the energy demand is covered by renewable energy sources (hydropower for electrical energy and biogas for thermal energy). With regard to acrylonitrile (ACN) as the starting monomer, according to Hohmann and Frank [31] its GWP can be reduced by 30% through the use of renewable energy sources and PtX. In this projection, it is assumed that this reduction potential is transferable to the comonomer and that both are exploited by 2050 in a linear adjustment process.	<table><thead><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr></thead><tbody><tr><td>2020</td><td>5.12</td></tr><tr><td>2030</td><td>4.78</td></tr><tr><td>2040</td><td>4.44</td></tr><tr><td>2050</td><td>4.10</td></tr></tbody></table>	Year	GWP in kg CO ₂ eq. per kg	2020	5.12	2030	4.78	2040	4.44	2050	4.10	
Year	GWP in kg CO ₂ eq. per kg													
2020	5.12													
2030	4.78													
2040	4.44													
2050	4.10													
C	Biobased material projection: The GWP of PAN precursor is reduced from 2030 by using biobased production routes for the ACN monomer. A technology mix of different biobased manufacturing routes is considered.	This projection is implemented by changing the GWP per kg precursor material in the background database with Wurst. The energy and material flows of the baseline value correspond to those of projections A and B. Based on this, the GWP reduction potentials per kg PAN precursor through the use of bio-based ACN based on bio-naptha, bio-methanol and e-methanol are assumed according to the information provided by Hohmann and Frank [31]. A gradual technology transformation path according to Hohmann [70] and a full exploitation of the identified potentials until 2050 are assumed.	<table><thead><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr></thead><tbody><tr><td>2020</td><td>5.12</td></tr><tr><td>2030</td><td>4.06</td></tr><tr><td>2040</td><td>3.55</td></tr><tr><td>2050</td><td>3.34</td></tr></tbody></table>	Year	GWP in kg CO ₂ eq. per kg	2020	5.12	2030	4.06	2040	3.55	2050	3.34	
Year	GWP in kg CO ₂ eq. per kg													
2020	5.12													
2030	4.06													
2040	3.55													
2050	3.34													
D	Renewable energy and biobased material projection: The combined use of renewable energy sources and PtX-technologies (projection B) as well as carbon capture and usage (CCU) technologies and biobased raw material (projection C) for the PAN precursor production leads to a significant reduction in the GWP of epoxy resin by 2050.	This projection is implemented by changing the GWP per kg precursor material in the background database with Wurst. Based on the projections B and C and the reduction potentials for biobased ACN production using renewable energy sources and PtX technologies given by Hohmann [70], the GWP per kg precursor is calculated. For the production routes of bio-based ACN via the bio-methanol and e-methanol routes, the use of CCU technologies is also assumed according to Hohmann and Frank [31, 70]. A gradual technology transformation path with a complete switch to biobased ACN based on the e-methanol route by 2050 is assumed in this projection according to Hohmann [70]. By using CCU, these assumptions can lead to a negative GWP in 2050 [70]. In order to avoid false conclusions for component development, such as using more of the precursor material to lower the GWP, the GWP of the precursor for 2050 is set to zero.	<table><thead><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr></thead><tbody><tr><td>2020</td><td>5.12</td></tr><tr><td>2030</td><td>3.87</td></tr><tr><td>2040</td><td>2.70</td></tr><tr><td>2050</td><td>0,00</td></tr></tbody></table>	Year	GWP in kg CO ₂ eq. per kg	2020	5.12	2030	3.87	2040	2.70	2050	0,00	
Year	GWP in kg CO ₂ eq. per kg													
2020	5.12													
2030	3.87													
2040	2.70													
2050	0,00													
E	Renewable energy and lignin precursor projection: By a technology switch from PAN as precursor material to lignin, the GWP of the precursor can be significantly reduced. The technology change to lignin precursor occurs in 2030.	This projection is implemented by changing the GWP per kg precursor material in the background database with Wurst. Based on the data for the GWP of the production of lignin-based carbon fibres provided in Hermansson [71], a baseline value of 3.90 kg CO ₂ eq. per kg lignin precursor is calculated. Taking into account the data on possible GWP reduction potentials in lignin-based carbon fibres in Hermansson [71] through the implementation of efficiency measures and the use of low carbon electricity, a reduction potential of 47% to 2.08 kg CO ₂ eq. per kg lignin precursor is calculated. It is assumed that this potential can be exploited between 2020 and 2050 through a linear adjustment process. It must be noted that the study by Hermansson [71] does not assume pure lignin precursors, but a combination of lignin (50 w.-%) and biobased polyurethane (50 w.-%) and that the results are highly sensitive to the allocation methods used for the lignin production process.	<table><thead><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr></thead><tbody><tr><td>2020</td><td>5.12</td></tr><tr><td>2030</td><td>3.29</td></tr><tr><td>2040</td><td>2.68</td></tr><tr><td>2050</td><td>2.08</td></tr></tbody></table>	Year	GWP in kg CO ₂ eq. per kg	2020	5.12	2030	3.29	2040	2.68	2050	2.08	
Year	GWP in kg CO ₂ eq. per kg													
2020	5.12													
2030	3.29													
2040	2.68													
2050	2.08													

2.6 Carbon fibre production	A	Baseline projection: The GWP of the carbon fibre manufacturing process based on precursor fibres does not change significantly between 2020 and 2050. Only the energy demand can be slightly reduced through efficiency measures.	This projection is implemented by changing the GWP per kg carbon fibre in the background database with Wurst. For the conversion process from precursor fibre to carbon fibre, which includes the steps of stabilisation, carbonisation and surface treatment, the baseline value and the underlying energy and material flows are based on the data provided by Hohmann [15], Dér et al. [17], Das [63] and Arnold et al. [16]. Based on this, it is assumed that from 2020 the energy consumption of all forms of energy is reduced linearly with 1% reduction per year. For values in the diagram on the right, the baseline scenario for the electricity mix was assumed.	<table><thead><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr></thead><tbody><tr><td>2020</td><td>17.87</td></tr><tr><td>2030</td><td>15.40</td></tr><tr><td>2040</td><td>15.04</td></tr><tr><td>2050</td><td>16.27</td></tr></tbody></table>	Year	GWP in kg CO ₂ eq. per kg	2020	17.87	2030	15.40	2040	15.04	2050	16.27
	Year	GWP in kg CO ₂ eq. per kg												
	2020	17.87												
	2030	15.40												
2040	15.04													
2050	16.27													
B	Renewable energy projection: The GWP of the carbon fibre manufacturing process is reduced from 2020 by using renewable energy sources. By 2040, a complete switch to renewable energy sources is achieved.	This projection is implemented by changing the GWP per kg carbon fibre in the background database with Wurst. Based on the energy demand data of Projection A, it is assumed that the energy demand can be fully covered by renewable energy sources by 2040, assuming a linear adjustment process. It is considered that the thermal energy demand is covered by biogas and the electrical energy demand by renewable electricity.	<table><thead><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr></thead><tbody><tr><td>2020</td><td>17.87</td></tr><tr><td>2030</td><td>12.28</td></tr><tr><td>2040</td><td>9.08</td></tr><tr><td>2050</td><td>8.19</td></tr></tbody></table>	Year	GWP in kg CO ₂ eq. per kg	2020	17.87	2030	12.28	2040	9.08	2050	8.19	
Year	GWP in kg CO ₂ eq. per kg													
2020	17.87													
2030	12.28													
2040	9.08													
2050	8.19													
C	Electrification and renewable energy projection: The GWP of the carbon fibre manufacturing process is reduced from 2020 through electrification of fossil fuel based heating processes and the use of renewable energy sources. Electrification and switch to renewable energy sources occur in a linear adjustment process to 100% by 2040.	This projection is implemented by changing the GWP per kg carbon fibre in the background database with Wurst. Based on the energy demand data of Projection A, it is assumed that the energy demand for heating processes can be covered by electricity in a linear adaption process to 100% by 2040. Starting in 2020 the consumption of natural gas is reduced linearly reaching zero in 2040. At the same time electricity is integrated as a new form of energy and the consumption of electricity is increased. As a simple assumption 1 kWh of natural gas is compensated by 1 kWh of electricity. The development of the greenhouse gas intensity of the electricity corresponds to that from projection B.	<table><thead><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr></thead><tbody><tr><td>2020</td><td>17.87</td></tr><tr><td>2030</td><td>7.32</td></tr><tr><td>2040</td><td>1.80</td></tr><tr><td>2050</td><td>1.78</td></tr></tbody></table>	Year	GWP in kg CO ₂ eq. per kg	2020	17.87	2030	7.32	2040	1.80	2050	1.78	
Year	GWP in kg CO ₂ eq. per kg													
2020	17.87													
2030	7.32													
2040	1.80													
2050	1.78													
D	Electrification, renewable energy and efficiency projection: The GWP of the carbon fibre manufacturing process is reduced from 2020 through electrification of heating processes, the use of renewable energy sources and the implementation of energy efficiency measures.	This projection is implemented by changing the GWP per kg carbon fibre in the background database with Wurst. In addition to the GWP reduction activities in carbon fibre production considered in projection C, it is assumed that the total energy demand can be reduced by 50% by 2050, for example through efficiency measures and technology innovations. In Hermansson et al. [30], an electricity-based conversion of precursor to carbon fibre by microwave heating is stated to have an energy saving potential of over 90 %, so that the assumed value of 50 % is relatively low. The electrification and switch to renewable energy sources occur as in projection C, the energy efficiency measures are implemented assuming a linear adjustment process until 2050.	<table><thead><tr><th>Year</th><th>GWP in kg CO₂ eq. per kg</th></tr></thead><tbody><tr><td>2020</td><td>17.87</td></tr><tr><td>2030</td><td>6.34</td></tr><tr><td>2040</td><td>1.76</td></tr><tr><td>2050</td><td>1.56</td></tr></tbody></table>	Year	GWP in kg CO ₂ eq. per kg	2020	17.87	2030	6.34	2040	1.76	2050	1.56	
Year	GWP in kg CO ₂ eq. per kg													
2020	17.87													
2030	6.34													
2040	1.76													
2050	1.56													

2.7 Recycled content	A	Moderate increase of secondary materials: Half of the theoretical potential for increasing secondary material usage from projection B is achieved.	This projection is implemented by changing the amount of primary and secondary material for each design variant in the foreground database with Wurst. It is assumed that only half of the improvements described in projection B until 2050 will be achieved.	Recycled content data from industrial processes are used as baseline values. These values cannot be published for reasons of confidentiality.
	B	Substantial improvement of secondary material usage: Secondary material content is increased according to theoretical potentials.	This projection is implemented by changing the amount of primary and secondary material (recycled content) for each design variant in the foreground database with Wurst. Different values for the possible recycled content are defined for the different materials: Steel: The usage of secondary steel for the production of steel coils is already considered in projections 2.1 A - C based on the underlying scenarios. Therefore, no additional consideration of the recycled content is necessary here. Aluminium: Based on the European Aluminium's Vision 2050 [29] a secondary aluminium share of 49% in the European production until 2050 is realistic. The gap between the current secondary share and the realistic share until 2050 is defined as possible improvement potential. The improvement potential is implemented linearly between 2020 and 2050. Prepreg: For the carbon fibre and the epoxy matrix it is assumed that a maximum of 20% recycled content can be reached until 2050. This value is based on the assumption that progress will continue to be made in the development of recycling and processing technologies for carbon fibres and matrix materials (see e.g. La Rosa et al. [77] and Ballout et al. [78]), so that recycled carbon fibres and matrix materials will increasingly be used in structural components.	
	C	Worst case projection: No changes of recycled content	No changes of the recycled content in the foreground database.	