Life Cycle Assessment

Comparison of solar-electric vehicles, between the thyssenkrupp SunRiser and the thyssenkrupp blue.cruiser

2017

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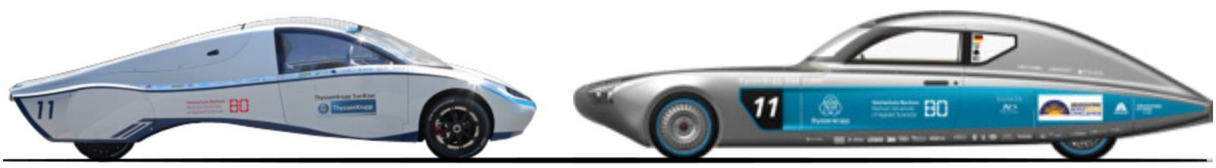

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Statement

This study has been conducted according to the requirements of this International Standard (ISO 14044).[1]

[1] DIN Deutsches Institut für Normung 2006

I. Abbreviation

°C *Degree Celsius*
µm *Micrometre*
Al_2O_3 *Aluminium oxide*
BC *blue.cruiser*, *blue.cruiser*
BMS *Battery management system*
CFC *chlorofluorocarbons; dt.: FCKWS*
CFRP Carbon fibre reinforced polymers
cm *Centimetre*
DC *Direct current*
DEC *Diethyl carbonate*, *Diethyl carbonate*
DMC *Dimethyl carbonate*
EAF *Electric arc furnace*, *Electric arc furnace*
EC *Ethylene carbonate*, *Ethylene carbonate*
eq. *equivalents*
g *Gramme*
GaAs *Gallium arsenide*
GaBi *Thinkstep GaBi Software*
GaInP *Indium gallium phosphide*
Ge *Germanium*
GFRP *Glass fibre reinforced plastic*
km *Kilometres*
km/h *Kilometres per hour*
kWh *Kilowatt hour*
LCA *Life Cycle Assessment / Life Cycle Analysis*
LCI *Life Cycle Inventory*
LCIA *Life Cycle Inventory Analysis*
$LiPF_6$ *Lithium hexafluorophosphate*
MJ *Mega joule*
mK *Metre-Kelvin*
NCA *Lithium nickel cobalt aluminium oxide*
NFRP *Natural fibre reinforced plastic*
NMP *N-Methyl-2-pyrrolidone*, *N-Methyl-2-pyrrolidone*
PAN *Polyacrylonitrile*
PMI Polymethacrylimide, *Polymethacrylimide*
$POCl_3$ *Phosphoryl chloride*
PP *Polypropylene*
PVC *Polyvinyl chloride*
PVDF *Polyvinylidene*, *Polyvinylidene fluoride*
SiO_2 *Silicon dioxide*
sqm *Square metre*
SR *SunRiser*, *SunRiser*
T *Tesla*
VOC *volatile organic compounds*

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V. Preface

Since the beginning of mankind, social, ecological, and economical influences affect the natural environment. These interventions have reached global dimensions; particularly climate change, biodiversity loss, soil degradation or the overexploitation of biologically-productive areas count as the most advanced and critical changes in the human and natural environment[2]. The amounts resulting from such environmental changes consequence a growing number of natural catastrophes, species extinction or food shortages and change human basis for life totally[3].

Not later than, with the arrival of the environmental movement in the 1970s, an increased thinking about the question, how much our well-being as well as our material prosperity are linked to an intact nature, started. Nowadays, topics of sustainability will never be missed in our everyday life, in political contests or in economy. The purpose of companies is not only in the production and marketing of their products. Increasingly, consumers want companies to have a social responsibility and expect environmentally and socially sustainable produced, packaged and distributed products.

Many companies and businesses have already begun to integrate environmental precautions in their production. Most of these measures focus on facility-level compliance and control. These reflections only relate to a small part of the product life cycle and therefore only show a small amount of a wide system. These considerations are not holistic and contradict sustainability thought, because a product or industrial activity exists not in isolation but rather as part of a complex system[4].

An important tool for sustainable product management is *Life Cycle Assessment* (LCA). A LCA is a systematic analysis of the environmental impacts of products throughout the life cycle (cradle to grave) or up to a certain time of processing (cradle to gate, gate to gate). The analysis includes total environmental impact during production, the use phase and disposal/recycling of the product, as well as the associated pre- and post-processes (e.g. preparation of raw materials and supplies)[5]. The target of LCA is to collect, to quantify and to identify these impacts, to find opportunities to reduce their environmental influences on the system under study.

[2] WBGU, 2013
[3] WBGU, 2005
[4] Graedel et al., 2003
[5] DIN EN ISO 14040, 2009

1 Starting position and problem setting

The global economy is directly linked to the natural system; if the natural system is influenced, this automatically results in a reciprocal impact of the global economy. Especially the mobility sector has a significant influence on climate[6]. Exactly for this reason it became necessary that after 120 years' automobile history, mankind must deal more intensively with environmental protection and resource conservation.

In the future, questions like:

- What should future mobility look like?
- What current concepts are being implemented?
- Where are the potentials for improving environmental efficiency in the product lifecycle of modern automobiles?
- How can I make sustainability visible?

must be answered.

The *SolarCar Project of University of Applied Science Bochum*[7] has been trying to answer these questions for over 15 years. It is a student project, where every 2 years a solar powered vehicle for the *Bridgestone World Solar Challenge*[8] is developed. In this competition, teams from all over the world challenge in different vehicle classes and try to face mobility of tomorrow. Seven solar cars have already been developed in this process, getting more suitable for everyday use. The vision of the current team is to make the production of the SolarCar as environmentally friendly as possible. The idea and motivation for the present bachelor thesis emerges from this context.

Within the framework of this comparative LCA study, the integration and implementation of a Life Cycle Assessment in the SolarCar Project should be investigated. First, the Goal and Scope Definition of a Life Cycle Assessment should be defined for the thyssenkrupp blue.cruiser. A suitable reporting framework should be selected for the emissions arising over the entire life cycle. Then the data required for Life Cycle Assessment study are collected and displayed.

The main goal of the work is the identification and evaluation of parameters which describe the object of observation and have a significant influence on its ecological effects.

All these objectives can be summarized under the heading *holistically*. A holistic view of challenges is an unconditional prerequisite for finding sustainable solutions.

[6] Stern et al., 2006
[7] For further information: www.bosolarcar.de
[8] For further information: www.worldsolarchallenge.org

2 Goal and scope definition

2.1 Goals

2.1.1 Reasons for conducting the study

Environmental pollution related to vehicles has been in the focus of public interest for many years. There is still a considerable political interest in further reducing the environmental impact of cars. The aim of environmental policy is,

- On the one hand, to promote ecologically advantageous vehicles[9],
- On the other hand, to achieve (ecological) optimization of vehicles, for example through innovations in material development.

As a decision preparation, an assessment of the environmental friendliness of various vehicles is necessary. In this case, not only individual environmental impacts (such as CO_2 emissions in use) are to be assessed, but a complete, holistic view of the environmental impacts along the entire life cycle of the respective car (raw material extraction, production, waste disposal, etc.) should be investigated. Life Cycle Assessments has become established as a suitable tool for such an approach.

The primary purpose of the study is to assess the environmental impacts of all new SolarCars and its components. The LCA should include all relevant life steps, like resource-depleting, refining, processing, transportation, use and recycling (i.e. cradle-to-grave). The study is intended to give up-to-date Life Cycle Inventory (LCI) data, modellings, and information, which can be used for further Life Cycle Assessments in the SolarCar Project, on conventional automobiles, and other vehicles. When it exists, the goal of LCA studies is to compare the new vehicle with its predecessor.

As this is a comparative study it consists of two objectives which are to be analysed and compared. These objectives are the thyssenkrupp SunRiser, a SolarCar constructed as a collegiate project of students and alumni at the Bochum University of Applied Sciences and finalized in 2015, and its successor, the thyssenkrupp blue.cruiser, finalized in 2017.

Additionally, this study is meant to disclose the environmental aspects, without including social impacts. It is hoped that the implementation and the results of this study will help to construct upcoming SolarCars more sustainable. Furthermore, it is hoped that this study motivates other SolarCar-Teams to build more sustainable vehicles.

With such an updated LCI database, the SolarCar Project, the automobile industry, and its suppliers can assist other organizations to better understand and communicate the environmental influences of manufacturing cars. At the same time, this database will help the industry to achieve a better understanding of its manufacturing processes, and identify potential areas for improvements.

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[9] For example: „Gesetz zur steuerlichen Förderung von Elektromobilität im Straßenverkehr“

With this new strategy, the automotive industry, its suppliers and other member companies are encouraged to think out about the conventional approaches, to get a clear overview and a better understanding of their own products.

2.1.2 Intended audience

This study is essentially conducted for the SolarCar Team of the Bochum University of Applied Sciences, its cooperation partner thyssenkrupp and the public large. The LCA is executed by students of the Bochum University of Applied Sciences in the framework of a pre-investment study of the degree course Sustainable Development. The LCA is oriented to several target groups with specific applications:

The SolarCar Project receives the opportunity to answer company-specific questions. E.g.:

- The display of the life phases allows the project to optimize existing manufacturing processes or to develop new manufacturing processes with better environmental benefits.
- The project obtains information about used resources and goods. This information can be used to increase efficiency, reduce costs, and help for the strategic planning of the next cycle.
- With the results of the investigation, SolarCar-Teams receive specific information about the potential for ecological improvements of electric vehicles.

The Federal Environmental Agency and the Federal Ministry of the Environment can use the results for consultation activities and for the scientific support of strategic decisions in the field of environmental protection.

Consumers and environmental organizations can use the results of the study as a basis (among others) for recommendations on the selection of electric cars.

LCA studies will be available to expert stakeholders to sustain the dialogue on life cycle management.

2.1.3 Use for the study

The results of this study can be used to:

- Show of up-to-date data on automobile components, in this case SolarCars;
- Improve the understanding on the environmental impact, which is generated by the production of cars;
- Show possible approaches for the improvement and optimization of the production of electric cars;
- Provide ideas for strategic planning of sustainable products;
- Enhance and promote the view of sustainable product entitlements.

2.2 Scope

The study is carried out in the form of Life Cycle Assessment and considers the requirements defined in DIN EN ISO 14040 to 14044

In the following, the Scope Definition for this Life Cycle Assessment, per DIN EN 14040, chap. 5.1.2 and 14041, is established.

2.2.1 Hotspots

An automobile (and of course a solar-powered vehicle also) consists of thousands of components, which in turn consist of different material compositions. The weight and the material composition were determined based on data collections sheets and stock lists. To get a targeted overview of the environment-critical materials of the solar cars, this study was conducted as a comparative hotspot analysis.

"Hotspots analysis is a methodological framework that allows for the rapid assimilation and analysis of a range of information sources, including life cycle based studies, market, and scientific research, expert opinion and stakeholder concerns. The outputs from this analysis can then be used to identify potential solutions and prioritize actions around the most significant economic, environmental, ethical and social sustainability impacts or benefits associated with a specific country, industry sector, organization, product portfolio, product category or individual product or service. Hotspots analysis is often used as a precursor to developing more detailed or granular sustainability information."[10]

The method of an ABC analysis is used to define the hotspots. The hotspots were identified by their mass fraction and their greenhouse gas potential (see Table 1-4). All coloured materials in the table are selected as hotspots for this LCA. Based on this definition the hotspots for the thyssenkrupp SunRiser include aluminium, carbon, neodymium, rubber, steel, gallium arsenide solar cells, lithium-ion batteries and ROHACELL®. For the thyssenkrupp blue.cruiser the hotspots stay mostly the same, except now the solar cells are made out of silicon. Furthermore, the material linen in combination with organic resin and hardener has been used in the newer SolarCar to partially replace carbon compounded with inorganic resin and hardener.

> Note: The bullet point *various* was not considered, since small components and auxiliary materials such as screws, sleeves, bolts, adhesives etc. are grouped together, which in individual cases, represent less than 0.5% of the total weight.

[10] UNEP/SETAC, 2014

Table 1: ABC analysis SunRiser weight

Material	Weight [kg]	Percentage [%]	CO_2-eq. [kg] / 1 kg material	CO_2-eq. Sun-Riser	Required quantity	Total CO_2-eq. [kg]	Category
CFRP	100.71	27.94	29.67	2988.07	1	2988.07	A
Various	21.20	5.88			1		
Battery	87.10	24.17	54.74	4767.85	1	4767.85	
Steel	33.21	9.22	2.14	71.11	1	71.11	
Aluminium	25.98	7.21	9.70	252.01	1	252.01	
Copper	31.9	6.05	2.80	89.32.	1	89.32	
ROHACELL®	13.57	3.77	4.62	62.70	1	62.70	B
GaAs solar cells	10.00	2.77	311.00	3100.00	1	3100.00	
Tyres	8.00	2.25	4.22	33.76	9	303.84	
Magnesium	5.20	1.44	34.80	180.96	1	180.96	
Plexiglas	4.10	1.17	3.80	15.96	1	15.96	
Contact sheets	4.10	1.14	7.52	30.83	1	30.83	
Electric compo-nents	2.90	0.80	3.86	11.19	1	11.19	
PVC	2.70	0.75	2.13	5.81	1	5.81	

Material	Weight [kg]	Percentage [%]	CO_2-eq. [kg] / 1 kg material	CO_2-eq. Sun-Riser	Required quantity	Total CO_2-eq. [kg]	Category
Flame protection coat	2.00	0.55			1		B
Synthetics	2.00	0.55	0.71	1.42	1	1.42	
PET	1.20	0.33	2.20	2.64	1	2.64	
Neodymium	1.20	0.33	27.00	32.40	1	32.40	
Circuit board	1.10	0.31	101.24	111.36	1	111.36	
Cork	0.90	0.25	-0.13	-0.12	1	-0.12	
Wood	0.90	0.25	-6.90	-6.21	1	-6.21	
Sinter metal	0.80	0.22			1		C
PU-glue	0.50	0.14	2.70	1.35	1	1.35	
Titanium alloy	0.10	0.03	8.10	0.81	1	0.80	
Balsa	0.00	0.00			1		
Nylon	0.00	0.00			1		
Total	360.37	100					
Total Hotspots	327.87	91.01					

Table 2: ABC analysis blue.cruiser weight

Material	Weight [kg]	Percentage [%]	CO_2-eq [kg]/1 kg material	CO_2-eq. blue.cruiser	Required quantity	Total CO_2-eq. [kg]	Category
CFRP	111.00	32.80	29.67	3293.37	1	3293.37	A
Steel	101.50	22.62	2.14	217.21	1	217.21	
Battery	81.59	17.49	54.74	4466.53	1	4466.53	
Various	35.40	7.60			1		
Aluminium	36.70	7.86	9.70	355.99	1	355.99	B
Copper	27.10	5.81	2.80	75.88	1	75.88	
NFRP	12.40	2.65	22.82	282.97	1	282.97	
Polyamide	9.40	2.01			1		
PET	9.33	2.00	2.20	20.52	1	20.52	
Tyres	8.15	1.74	4.22	34.39	9	309.54	
ROHACELL®	8.08	1.73	4.62	37.33	1	37.33	
Plexiglas	6.24	1.33	3.80	23.71	1	23.71	
Si solar cells	3.65	0.78	306.48	1118.64	1	1118.64	C
PVC	3.56	0.76	2.13	7.61	1	7.61	
Nylon	3.00	0.64			1		
Neodymium	1.76	0.38	27.00	47.52	1	47.52	
Insulator	1.69	0.36			1		
Adhesive	1.60	0.34	2.70	4.32	1	4.32	
Titanium	1.50	0.32	8.10	12.11	1	12.11	
Brake fluid	1.00	0.21			1		
Cork	0.69	0.15			1		
Circuit board	0.41	0.08	3.86	1.60	1	1.60	
Iron	0.40	0.08			1		
Coating	0.20	0.04			1		
Brass	0.02	0.00			1		
Total	466.37	100					
Total Hotspots	402.14	86.22					

Table 3: ABC analysis SunRiser CO2-eq.

Material	Weight [kg]	Percentage [%]	CO_2-eq. [kg] / 1 kg material[11]	CO_2-eq. SunRiser	Required quantity	Total CO_2-eq. [kg]
Battery	87.10	24.17	54.74[12]	4767.85	1	4767.85
GaAs solar cells	10.00	2.77	311.00	3100.00	1	3100.00
CFRP	100.71	27.94	29.67	2988.07	1	2988.07
Tyres	8.00	2.25	4.22	33.76	9	303.84
Aluminium	25.98	7.21	9.70	252.01	1	252.01
Magnesium	5.20	1.44	34.80	180.96	1	180.96
Circuit board	1.10	0.31	101.24	111.36	1	111.36
Steel	33.21	9.22	2.14[13]	71.11	1	71.11
ROHACELL®	13.57	3.77	4.62	62.7	1	62.7
Neodymium	1.20	0.33	27.00	32.40	1	32.40
Contact sheets	4.10	1.14	7.52	30.83	1	30.83
Plexiglas	4.10	1.17	3.80[14]	15.96	1	15.96
Electric components	2.90	0.80	3.86	11.19	1	11.19

[11] If not otherwise marked, the data are from *GaBi* 2017
[12] Ellingsen *et al.* 2014
[13] Fraunhofer 2012, 30
[14] EVONIK 2015, 3

Material	**Weight [kg]**	**Percentage [%]**	**CO_2-eq. [kg] / 1 kg material[11]**	**CO_2-eq. Sun-Riser**	**Required quantity (usage scenario)**	**Total CO_2-eq. [kg]**
PVC	2.70	0.75	2.13	5.81	1	5.81
PET	1.20	0.33	2.20[15]	2.64	1	2.64
Synthetics	2.00	0.55	0.71	1.42	1	1.42
PU-glue	0.50	0.14	2.70[16]	1.35	1	1.35
Titanium alloy	0.10	0.03	8.10	0.81	1	0.80
Comb	0.90	0.25	-0.13	-0.12	1	-0.12
Wood	0.90	0.25	-6.90	-6.21	1	-6.21
Various	57.30	15.90			1	
Copper	31.9	6.05	2.80	89.32	1	89.32
Flame protection coat	2.00	0.55			1	
Sinter metal	0.80	0.22			1	
Balsa	0.00	0.00			1	
Nylon	0.00	0.00			1	
Total	360.37	100				
Total Hotspots	327.87	91.01				

[15] Detzel *et al.* 2004
[16] PlasticsEurope 2012

Table 4: ABC analysis blue.cruiser CO2-eq.

Material	Weight [kg]	Percentage [%]	CO2-eq [kg]/1 kg material[11]	CO2$_2$-eq. blue.cruiser	Required quantity	Total CO_2-eq. [kg]
Battery	81.59	17.49	54.74[12]	4466.53	1	4466.53
CFRP	111.00	32.80	29.67	3293.37	1	3293.37
Si solar cells	3.65	0.78	306.48	1118.64	1	1118.64
Aluminium	36.70	7.86	9.70	355.99	1	355.99
Tyres	8.15	1.74	4.22	34.39	9	309.54
NFRP	12.40	2.65	22.82	282.97	1	282.97
Steel	101.5	22.62	2.14[13]	217.21	1	217.21
Neodymium	1.76	0.38	27.00	47.52	1	47.52
ROHACELL®	8.08	1.73	4.62	37.33	1	37.33
Plexiglas	6.24	1.33	3.80	23.71	1	23.71
PET	9.33	2.00	2.20	20.52	1	20.52
Titanium	1.50	0.32	8.10	12.11	1	12.11
PVC	3.58	0.76	2.13	7.61	1	7.61
Adhesive	1.60	0.34	2.70	4.32	1	4.32
Circuit Board	0.41	0.08	3.86	1.60	1	1.60
Various	35.40	7.60			1	
Copper	27.10	5.81	2.80	61.04	1	61.04
Polyamide	9.40	2.01			1	
Nylon	3.00	0.64			1	
Insulator	1.70	0.36			1	
Brake fluid	1.00	0.21			1	
Cork	0.69	0.15			1	
Iron	0.40	0.08			1	

Material	Weight [kg]	Percentage [%]	CO2-eq [kg]/1 kg material	CO2$_2$-eq. blue.cruiser	Required quan-tity	Total CO_2-eq. [kg]
Coating	0.20	0.04				
Brass	0.02	0.00				
Total	466.37	100				
Total Hotspots	402.14	86.22				

2.2.2 Product systems under study

The product system under study is roughly shown in Figure 1. To be more precise, the product system under study, with its processes and life cycle stages, is depicted in Figure 2.

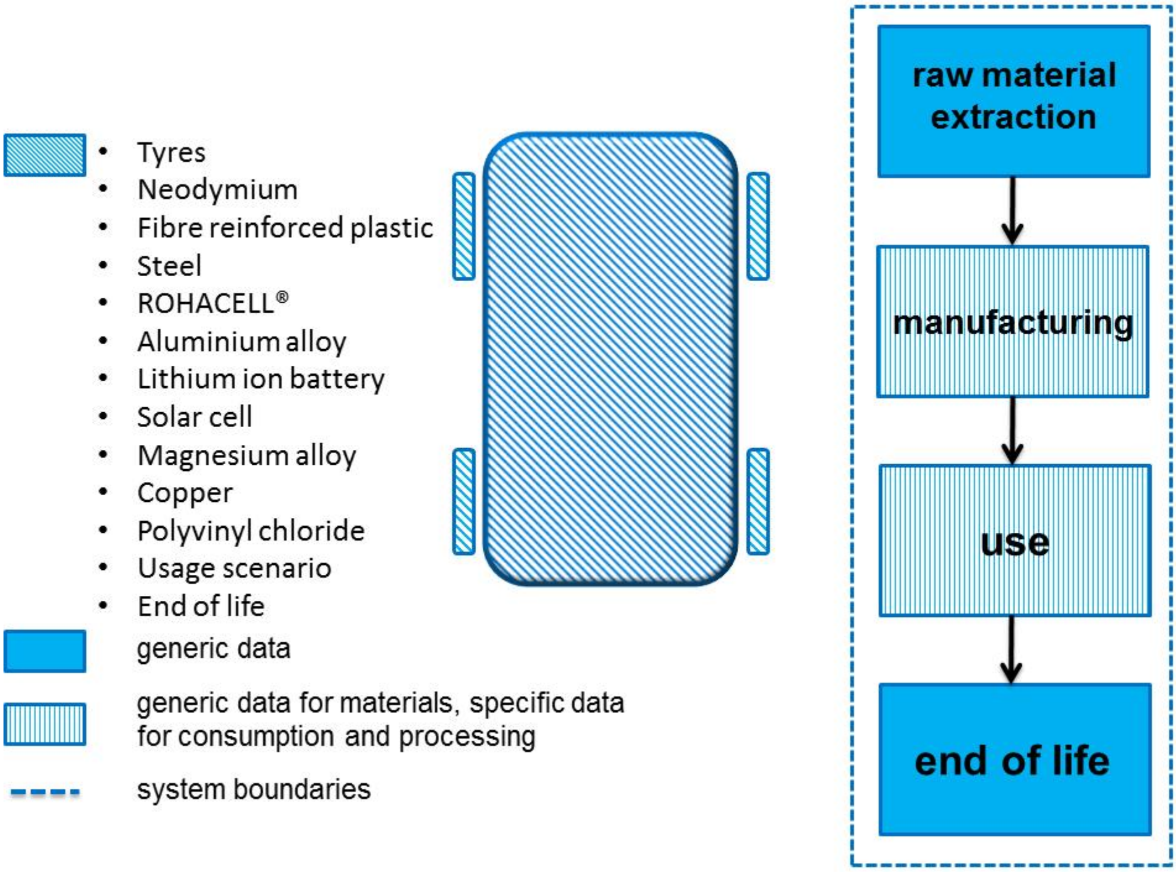

Figure 1: Schematic presentation of the system under study; own representation

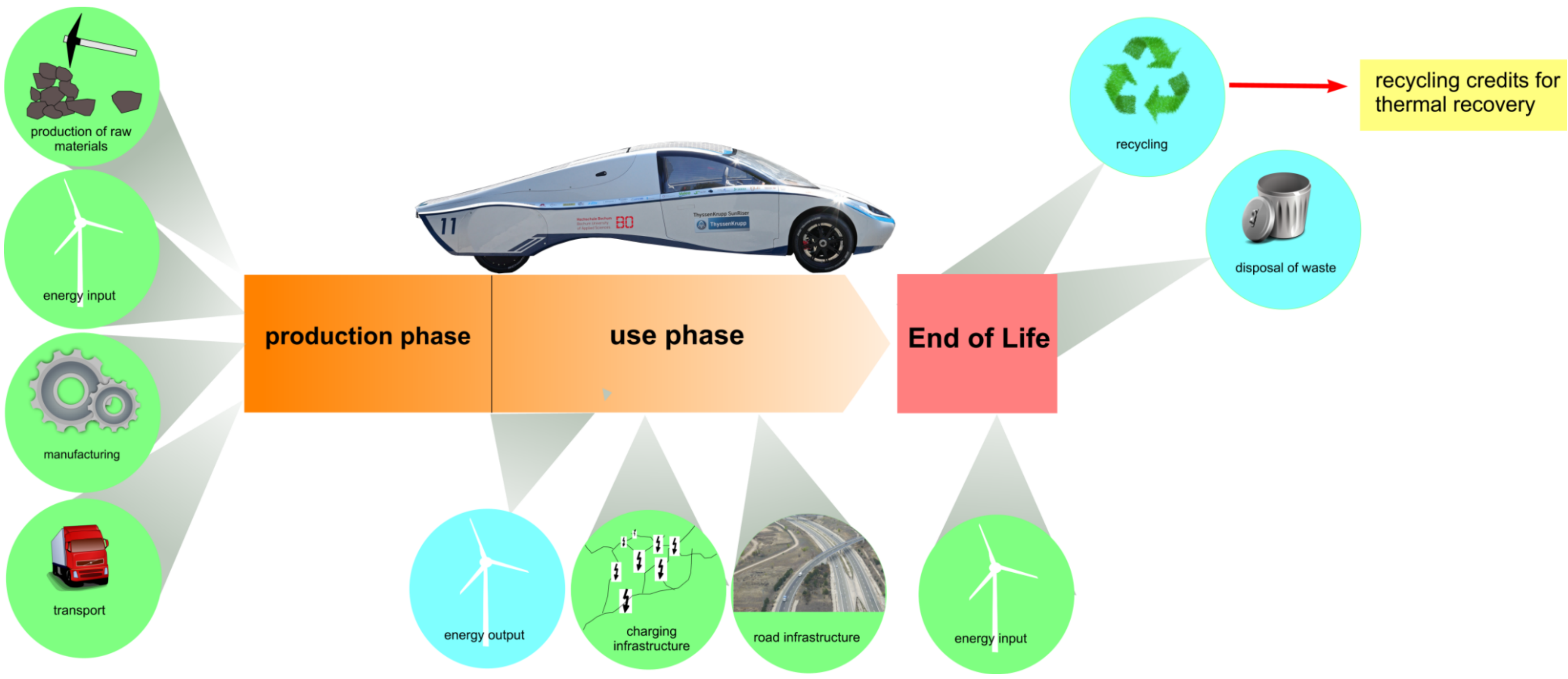

Figure 2: System boundaries; own representation

2.2.3 System function and functional unit

The functional unit is set to be one solar-powered vehicle. A solar-powered vehicle, hereafter referred to as solar car, is an electric car, which converts sun energy into electric energy using the principles of the photovoltaic effect. As can be seen in Figure 3, solar cars are roof-mounted with solar cells, which could generate the energy demand, that in favorable circumstances a solar car drives energy self-sufficient. Generally, solar cars are invented to participate at the Bridgestone World Solar Challenge in Australia.

The solar car must meet the safety and technical requirements of the New European Driving Cycle, drives fully occupied and must exceed 182.500 km[17] over a life time of 10 years.

In other words, it is defined as the electrical transportation of at least 2 persons (for the SunRiser; 4 persons at blue.cruiser) in a vehicle, for a total distance of 182.500 km, for 10 years, in compliance with type approval regulation of the New European Driving Cycle[18, 19, 20].

Figure 3: solar-powered vehicle

Solar-powered vehicles are designed for the world championship in Australia and therefore differ from conventional cars. They are electrical racing cars with road approval, less weight and low aerodynamic drag. The vision of University of Applied Science Bochum is to use the solar cars after the world championship for car sharing, which is why features such as heaters, storage space or 2-4 seats are installed in the cars.

The reporting units are in line with the global convention of Life Cycle Inventory and Impact Assessment reports, which are unified to metric units[5]. To explain, energy is in mega-joules (MJ), mass is in kilograms (kg) or metric tons (t), liquid volume is in liters (l), gaseous volume is in cubic meters (m^3), electricity is in megawatt-hours (MWh), a distance is measured in meters (m) or kilometers (km), a concentration in parts-per-million (ppm), etc.

[17] See 3.2.14 Usage scenario
[18] Renault Twingo, 2015
[19] Renault Espace, 2015
[20] Schweimer & Levin, 2000

2.2.4 System boundaries

All the environmental aspects of the SolarCar vehicles under consideration are evaluated *from cradle to grave*, that means from the exploration of the raw materials, to the manufacture of semi-finished products and components, distribution processes, to the disposal per the above-described life cycle model.

All inputs and outputs of the reported system, except for secondary raw materials (waste for recovery), secondary energy sources, and auxiliary and operating materials according to the cut-off criteria described below, are elementary flows, i.e. substances that are extracted from the natural environment or are delivered to the natural environment.

Exceptions which are not considered:

- Environmental impacts of the end users of the SolarCars, since they could not be collected within the framework of this project (for example, emissions and energy consumption due to distribution);
- Environmental impacts of the C-class products (see chapter 2.2.1 Hotspots);
- Environmental impacts from the production and disposal of investment goods along the life phase (e.g. energy consumption and emissions from the production of manufacturing machines);
- Environmental impacts from the maintenance of equipment;
- Environmental impacts of the varnishing of the finished body or the covering the seats;
- Social aspects such as fair salaries or good working conditions;
- Working hours and personnel expenses.

The following cut-off-criteria were defined by the DIN EN ISO 14040 *1%-rule*:

- *“Mass – If a flow is less than 1% of the cumulative mass of all the inputs and outputs (depending on the type of flow) of the LCI model, it may be excluded, provided its environmental relevance is not a concern.*
- *Energy – If a flow is less than 1% of the cumulative energy of all the inputs and outputs (depending on the type of flow) of the LCI model, it may be excluded, provided its environmental relevance is not a concern.*

- *Environmental relevance – If a flow meets the above criteria for exclusion, yet is thought to potentially have a significant environmental impact, it will be included. All material flows which leave the system (emissions) and whose environmental impact is higher than 1 % of the whole impact of an impact category that has been considered in the assessment, is covered.*
- *The sum of the neglected material flows shall not exceed 5% of mass, energy or environmental relevance*[5, 21].

Further cut-off criteria (e.g. for energy input or output materials) are not determined.

The description of the data used for mapping the sub processes is specified in chapter *3 Inventory analysis.*

2.2.5 Allocation

The allocation, used in the GaBi database, is retained in the background system. In the foreground system, a relevant allocation issue arises in the recycling of the materials used in the SolarCar. So, allocation has been avoided by expanding system boundaries and with the substitution of the input material.

Each LCI dataset including scrap, dross or recyclable goods was looped, so that the only valuable products exiting in the system are finished or semi-finished products. The applied concept is called *avoided burden approach*[21, 22].

The waste treatment of non-hazardous solid waste is considered as thermal and electrical energy generation. To avoid any allocation, the generated thermal and electrical energy is directly re-introduced in the LCI model. This approach reduces the energy demand significantly and closes the circulation[21, 22].

2.2.6 Method of impact assessment and interpretation

DIN EN ISO 14044 requires that the categories of the Impact Assessment are in line with the Goal and Scope Definition of the Life Cycle Assessment and that it reflects *"the environmental mechanism and characterization model that relate the LCI results to the category indicator"*[5].

Several environmental issues could emerge if the whole process of a product is investigated, from the very beginning until the recycling process. All these potential issues are reflected in the impact assessment.

[21] The Aluminum Association, 2013
[22] Nicholson et al., 2009

The main task of an impact assessment is to examine the data obtained in the factual balance sheet with regard to certain environmental impacts and thus provide additional information. The selected environmental impacts are called impact categories. The impact assessment method CML 2001 is based on the internationally accepted methods and data collected by the Centrum voor Milieuwetenschappen (CML) in Leiden. CML 2001 is a prominent and widely accepted method for classification and characterization for conducting LCAs. CML 2001 is a multidimensional approach for life cycle assessment, which results are grouped uses a midpoint approach. ISO 14044 does not provide a fixed list of impact categories[23].
The most discussed environmental effects related to mobility and automotive manufacturing are surely global warming, the consumption of finite resources for energy supply, ozone load and ozone depletion, and soil and water stress[18, 19, 20]. The following categories were selected for the presentation and evaluation:

a) Resource-related categories
   - Abiotic depletion potential

b) Emission-related categories
   - Global warming potential (100 years) inclusive biogenic carbon
   - Ozone Layer Depletion Potential
   - Photochemical Ozone Creation Potential
   - Acidfication Potential
   - Eutrophication Potential

c) Toxicity-related categories
   - Human Toxicity Potential
   - Ecotoxicity (freshwater)

The resource-related category is of interest due to the possible depletion of elements with high importance for the industrialized society, for example fossil fuels and rare metals used in electronics.
The category abiotic depletion potential refers to the consumption of non-biological resources such as fossil fuels. The value of the abiotic resource consumption of a substance is a measure of the scarcity of a substance. That means it depends on the amount of resources and the extraction rate. "*It's formed by the amount of resources that are depleted and measured in MJ of fossil fuels*." [24]

Emission-related categories are called the output-related effect categories. The output-related effect categories refer to the environmental impacts of emissions. These include the threat to human health and environmental pollution.

[23] DIN Deutsches Institut für Normung 2006
[24] Aitor P. Acero, Cristina Rodríguez, Andreas Ciroth 2016

The Global Warming Potential for a reference period of 100 years: The GWP in consequence of anthropogenic greenhouse emissions is the main cause of global warming. It is the most important impact category, especially since many natural effects such as tsunamis, hurricanes, and unusual weather conditions are based on this environmental effect. Several gases, inter alia carbon dioxide and nitric oxides contribute to the Global Warming Potential and are weighted differently in compliance with the CML baseline 2001 method. The characterization unit of GWP is stated in *kg or t* CO_2*-eq.*, so the carbon dioxide is the standardization parameter and the most important element of this category[25, 26].

Stratospheric Ozone Depletion: ODP describes a strong thinning of the ozone layer, as can be seen in the Antarctic. The main reasons for this depletion are various chemical and physical processes in the environment. The causes of ozone depletion are primarily free-radical chlorine atoms from chlorinated organic compounds, which are collectively referred to as chlorofluorocarbons (CFCs). At this altitude, the ozone molecules largely absorb the UV radiation of the sun, which is very harmful to all living cells. The different gases that contribute to this impact category are summarized under *kg R11-e.*[25, 26].

Summer Smog: The POCP labels a high concentration of ground-level air with harmful ozone gas, which is health hazardous to human, animal, and plants. The main reasons for this Summer Smog, which can generally be translated with air pollution, are various chemical and physical processes in the environment. The different gases that contribute to this impact category are summarized under *kg Ethene-eq.*[25, 26].

Acidification Potential: Acidification is an environmental effect resulting in a too low pH-level of soil or water. The best-known effect is the acid rain, which can be formed by emission of, e.g. ammonia, sulfur oxide or nitrogen oxides. The agricultural sector suffers most under acidification, as plant growth and soil fertility are restricted. The specific unit of this impact category is normalized to *kg SO2 eq.*[25, 26].

Eutrophication Potential: Eutrophication means over-fertilization resulting from too much nutrient supply and consequently increased oxygen consumption. Human causes eutrophication. A distinction is made between aquatic and terrestrial eutrophication. In this impact category, ammonia, nitrate (N-compounds) and phosphate (P-compounds) are the leading causes. All these substances are converted into the PO_4*-eq*.[25, 26].

[25] Danish Ministry of the Environment, 2005
[26] For further information: wirtschaftslexikon.gabler.de/Archiv/222023/cml-methode-v5.html

Freshwater Ecotoxicity: Freshwater ecotoxicity describes the potential for biological, chemical or physical stressors to affect the ecosystems. These stressors might occur in the natural environment to disrupt the natural biochemistry, behaviour and interactions of the living organisms that comprise the ecosystem. The emission of some substances, such as heavy metals, can have impacts on the ecosystem. Ecotoxicity potentials are calculated with the method for describing fate, exposure and the effects of toxic substances on the environment. These characterisation factors are expressed using the reference unit, kg 1.4-dichlorobenzene equivalent (1.4-DB)[27].

2.2.7 Data requirements

The framework definition for the geographical, temporal, and technological coverage of data used as well as their evaluation is described below. In this context, reference is made to relevant aspects for data quality, such as the detailed depth or the representativeness of the data.

Temporal Coverage: Primary data collected from the SolarCar Project and participating companies for their operational activities are representative for the year 2015 (reference year). Additional data for the modelling process were obtained from the GaBi 7 software system database (e.g. generic data for material production).

Geographical Coverage: The geographical coverage is Germany.

Technological Coverage: The LCA demonstrates the current technological possibilities for the production and fabrication of a solar-powered vehicle.

[27] Cf. breglobal

3 Inventory analysis

3.1 Validation of data

During the collecting process of data, it is necessary to validate the quality, which means to review the hotspots which were chosen. Table 5 shows the quality classification. The processes from the background system were obtained from GaBi ts 7 database. GaBi ts 7 is a modulation software which can perform, inter alia, life cycle inventory and impact assessment. The software contains a database with specific life cycle information of materials, production processes, disposal methods, etc. In case of inadequately data in the software we took additional data from other sources to get better results.

Table 5: Quality of data

Hotspot	Data specification			Data source	Comments
	Product specific	Specific to site	General		
Tyres		x		Thinkstep	The GaBi software was supplied with data from a general composition of a car tyre
Neodymium			x	Sprecher *et al.* 2014 Thinkstep	Data from the LCA were added to the GaBi software
Carbon fibre reinforced plastic		x		Thinkstep	Carbon fibres and resins were available in the software
Natural fibre reinforced plastic	x			Data sheets Thinkstep	Data sheets of the supplier and the Lamination[28] list were used to equip the GaBi software
Steel	x			thyssenkrupp Thinkstep	Good availability of data
PMI foam			x	Experts Thinkstep	Expert opinion [29] about the composition
Aluminium alloy	x			Thinkstep	Good availability of data

[28] For more detailed information, see 3.2.4 Natural fibre reinforced plastic
[29] Prof. Dr. rer. nat. Anke Nellesen, Bochum University of Applied Sciences

Hotspot	Data specifica-tion			Data source	Comments
	Product specific	Specific to site	General		
Triple Junction solar cell			x	ProBas, Thinkstep	Because of data-based insufficiency with regard to the Triple Junction solar cell, the Silicon solar cell was used as the basic model.
Magnesium alloy	x			Thinkstep	Data from the Thinkstep software
Copper	x			Thinkstep	Good availability of data
PVC	x			Thinkstep	Good availability of data
Notes: Product specific data: refers to processes specifically referring to vehicle. Site specific data: concern data from sites involved in the vehicle production but not specific to the vehicle. General data: all remaining data					

3.2 Hotspots

3.2.1 Tyres

Tyres are responsible for the road grip. That is why they are existentially important for driving characteristics of the vehicle. Tyres consist of various materials. The massive amount of weight makes tyres a hotspot in the LCA.

Table 6: Composition of a tyre [30]

Ingredient	Passenger Car Tyre
Natural Rubber	14%
Elastomers	27%
Carbon Black	28%
Steel (average)	15%
Textile (average)	6%
Zinc Oxide	0.83%
Softener and Chemicals	10%

Natural rubber is an amorphous polymer which is extracted from plants or trees. To extract the water out of the latex (the sap of the Hevea brasiliensis tree) ammonia is used[31]. Elastomer is synthetic caoutchouc, which means that the resource is natural

[30] Feraldi *et al.* 2013
[31] Cf. Gooch 2007

(oil) and there are many steps needed in production to get the product[32]. Carbon Black is mainly carbon in form of extremely fine particles. For tyres or other rubber compounds it takes the function of filler. Silicia can be used as partial substitute for Carbon Black in some types of tyres. These fillers are used to improve the lifetime or the rolling resistance[33]. Textile and Metal are layers which reinforces the structure of the tyre. Zinc Oxide is used for the vulcanization of the caoutchouc[34].

Vulcanization means "*the process of conversion of raw rubber composed of linear molecules to lightly crosslinked network*"[35]. Vulcanisation improves properties of the raw rubber. For example, this action increases stiffness and reduces the possibility of permanent deformation[36].

Some of the materials are mixed and stacked as it is shown in Figure 4: Tyre production and Figure 5: Tyre schema.

In the usage scenario, it is assumed that the SolarCar will last 10 years, while it drives 182,500 km. The SolarCar uses special tyres of Michelin and Schwalbe.

The racing tyres did not last long, according to an assumption of an expert from the SolarCar team[37] the Michelin Tyres last for 1,000 km and the one from Schwalbe 5,000 km. The tyres which are used in the chosen scenario are close to motor bike tyres because motor bike tyres are like the racing tyres of Schwalbe and Michelin. Motor bike tyres usually last for about 10,000 km, but have a higher road grid.

Our assumption is that the SolarCar tyres will last for 20,000 km. That is because the torque is lower, the weight is spread over the four tyres and the SolarCar has a two-wheel or a four-wheel drive.

That means 36 tyres are needed. The weight of one tyre used on the SolarCar is about 2 kg as it is exactly shown in Table 1: ABC analysis SunRiser weight and Table 2: ABC analysis blue.cruiser weight. That means during the phase of use the total weight of the tyres will be around 72 kg.

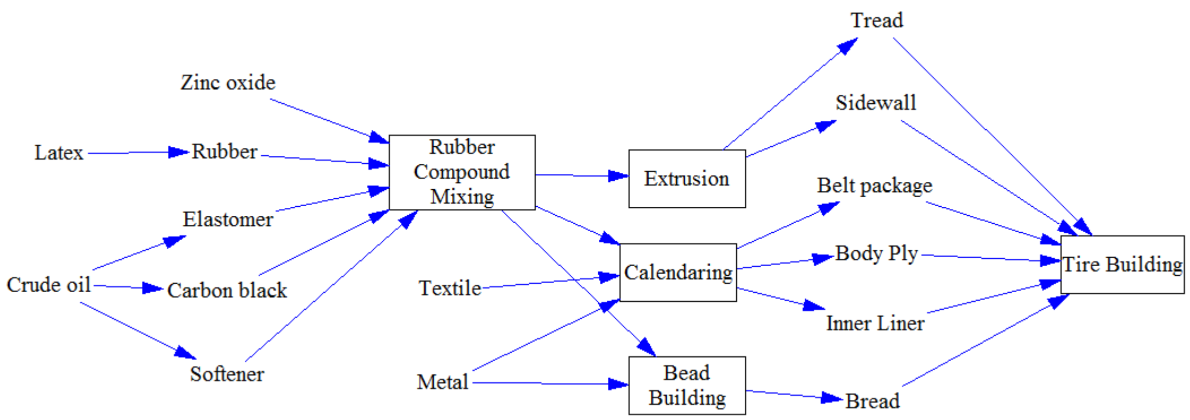

Figure 4: Tyre production

[32] Cf. Abts 2007
[33] Cf. Norman
[34] Cf. Wortmann *et al.* 2013
[35] Alger 1997
[36] Cf. Alger 1997
[37] SolarCar employee Matthias Wiemers

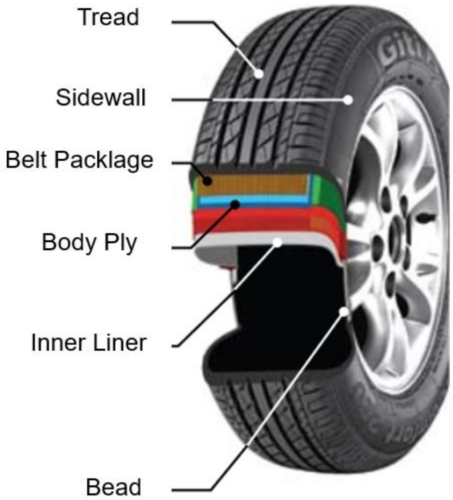

Figure 5: Tyre schema[38]

Recycling of scrap tyres is mainly done in two different ways: Material recycling or energy recovery. Within a mechanical process rubber granulate is produced in material recycling, this granulate can be used e.g. for road asphalt. Material recycling also means using the steel component to produce secondary steel. Energy recovery is to burn the tyres and use the energy. Primarily the scrap tires are a „*co-incineration at a cement kiln, where tyre material displaces conventional cement kiln fuels, bituminous coal and petroleum coke, as well as iron ore resources.* “[39].
The entire modelling of the tyres is shown in Figure 6: Tyres flowchart in GaBi.

[38] Giti Tire
[39] Associates/Genan 2010

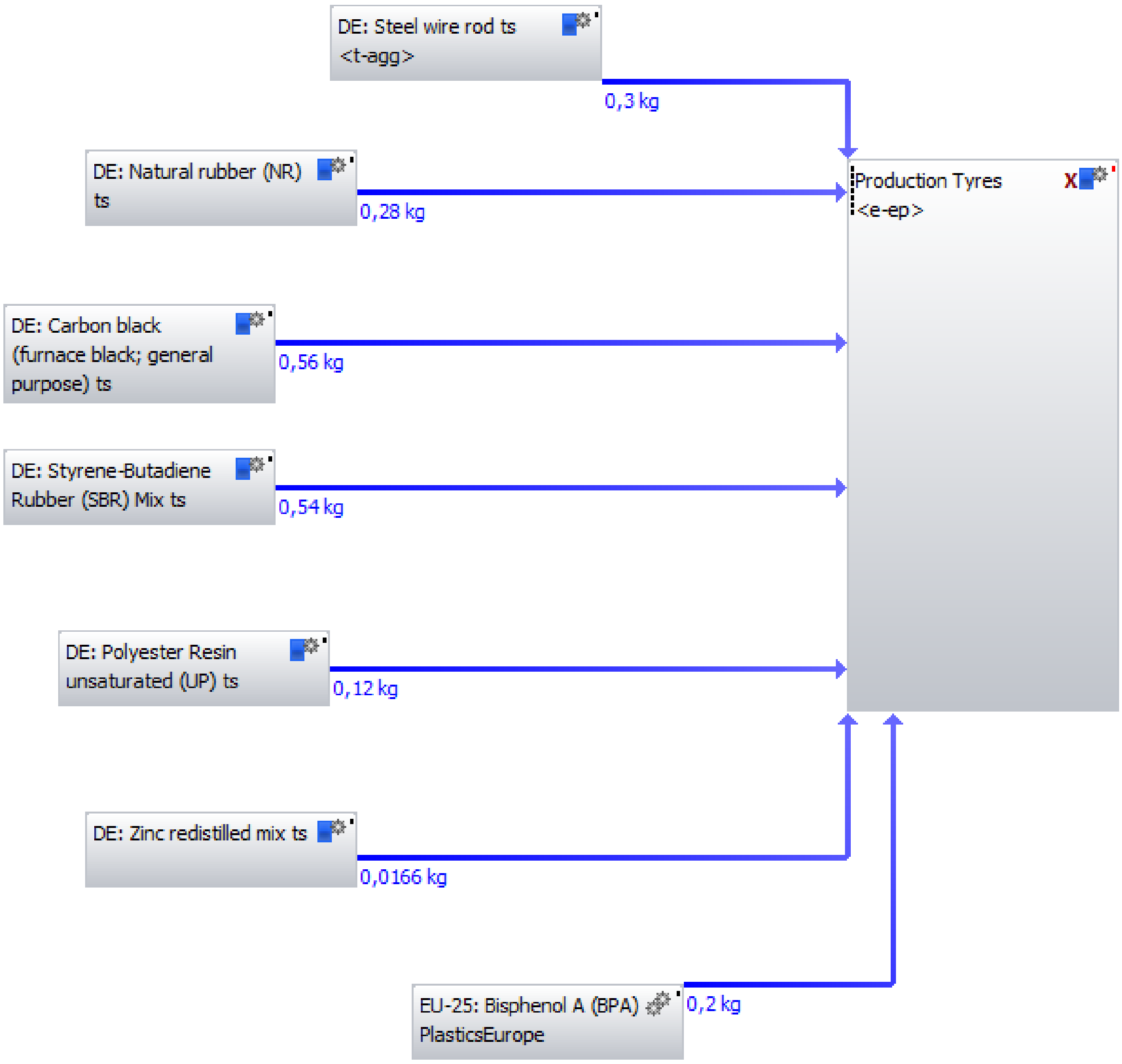

Figure 6: Tyres flowchart in GaBi

3.2.2 Neodymium

Neodymium magnets are the strongest of all rare earth magnets that exist today[40]. They have a high resistance to demagnetization. In fact, this makes them very useful in many kinds of industrial applications. The magnets used in the SolarCar are a special $Nd_2Fe_{14}B$ (Neodymium: 29-32%, Ferrite: 62-68%, Boron: 1-1.2%, Niobium: 0.5-1%, Dysprosium: 0.8-1.2%)[41] alloy. These magnets develop enough power to attract 1300 times of its own weight That is a remanence value between 1.3 T (Tesla) up to 1.6 T. NdFeB magnets have a low working temperature and the best way to use them is to coat the magnets for long-term energy output and usage.

40 Vgl. ThyssenKrupp Magnettechnik
41 Cf. Supermagnetic 2015

Neodymium magnets are referred to as rare earth magnets, because of their status in the periodic table. Another important factor for buying neodymium magnets is the affordability, so they are priced at a low level and so affordable for educators and experimenters on their limited budgets (83-86$/kg in 2016[42]).
Producing neodymium magnets needs a few steps, including mining, transport and manufacturing. The main mining areas are China, the United States and Brazil. The mining process includes a complex chemical separation from secondary materials, usually rocks. The next step is converting the oxide to neodymium fluoride. To get the final resource, the fluoride will be connected with calcium fluoride. To produce a complete magnet, different firms, mostly in China[43], are using time consuming methods. At first, iron, neodymium and boron are pulverized and fused together in a vacuum. This powder will be pressed in a cylindrical form and heated up. Next step, sintering is a common process in powder metallurgy[44]. The material is compressed at elevated temperatures (as high as 1080°C) below the material's melting point, until its particles adhere to each other.
After cooling down, the alloy has a crystal structure that benefits a magnetization later on. The next step is sawing the raw magnets into desired size. Thereafter, the magnets will be galvanically coated, usually with Nickel (Ni) or Copper and Nickel (Ni- Cu-Ni), otherwise, the magnets will demagnetize and are completely useless when the temperature rises over 80 degrees.
At this point of production, the magnets have a „preferred“ direction of magnetization, so the final step is to magnetize them completely: the raw magnets will be placed in a magnet coil, through which a strong electrical current is shot for one millisecond. A magnetic field outputs are neodymium magnets[45].

After a quality control, which includes verifying the magnetization and the coating thickness, they will ship in plastic bags and cardboard boxes around the world.
Besides many industrial uses, Neodymium magnets are very important in the SolarCar. To work inside the SolarCar the magnets are installed in the rotor. When an electric current is induced in the coil (stator), it emits a magnetic field, opposing the magnetic field emitted by the strong magnets (rotor). This repulsion causes the rotor to spin or rotate at a high speed. The wheel is attached to an axle that allows the wheels to move. The schematic structure of a SolarCar wheel hub engine can be seen in Figure 7: Basic structure of wheel hub engines using the example of SolarCar D-Type.

[42] Cf. Institut für seltene Erden und Metalle 2016
[43] Cf. VDI Verlag GmbH 2014
[44] Cf. K&J Magnetics
[45] Cf. K&J Magnetics

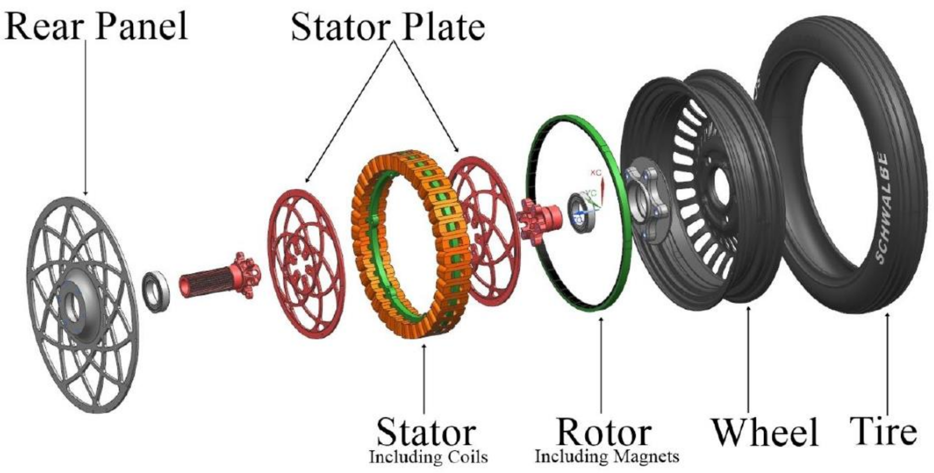

Figure 7: Basic structure of wheel hub engines using the example of SolarCar D-Type

The weight of one neodymium magnet is 0.0022kg. The four engines of the thyssenkrupp blue.cruiser are using 200 of them. That is a total weight of 1.76kg and 0.122% of the overall weight (see Table 1: ABC analysis SunRiser weight and Table 2: ABC analysis blue.cruiser weight). Main reasons to decide neodymium as a hotspot are the environmental results of mining. While mining neodymium, different secondary products spring up, including uranium and thorium. These by-products partially seep into the ground water.[46]

Unused, intact or obsolete Neodymium magnets can be demagnetized and returned to valuable raw material, which can be used for producing new magnets. It is possible to pry out the magnets out of the engine. After this shredding process, the neodymium needs to be leached out of the fragments, which are sticks together.

3.2.3 Carbon fibre reinforced plastic

Particularly carbon fibre reinforced polymers (CFRP) are a fibre-reinforced composite which is tight-connection and solid despite the slight weight and the slight density. CFRP was mainly chosen as a hotspot due to the high proportion of weight and, consequently, the high CO_2 emissions. Furthermore, the production is energy-intensive and it is costly to recycle[47].

Carbon fibres and resins are the basic materials to produce CFRP. Through various thermal treatment steps (stabilization and carbonization), carbon fibres are obtained from polyacrylonitrile (PAN) precursor fibres[48]. About 250 degrees Celsius are required for the stabilization and for the carbonization up to 1000 degrees Celsius. For this reason the production of carbon is energy-intensive[49]. The roving is processed to woven fabrics with the twill weave which are incorporated into a thermosetting matrix. The technique which is used in the solar car is the hand lay-up operation with vacu-

[46] Norddeutscher Rundfunk 2011
[47] Cf. Marilyn Minus
[48] Cf. Matthias Achternbosch 2002, 3
[49] Cf. Marilyn Minus, 53

um curing because in the process are minimum technical requirements adequate. Curing occurs at a maximum of 1 bar, which is air pressure, at 40 degrees Celsius (see Figure 8: CFRP production)[50]. The hardeners are aliphatic amines for which hexamethylenediamine is used in GaBi, because it has the same starting product. The coating of CFRP is made of glass fibres, which are included in the model (see Figure 9: CFRP flowchart in GaBi).

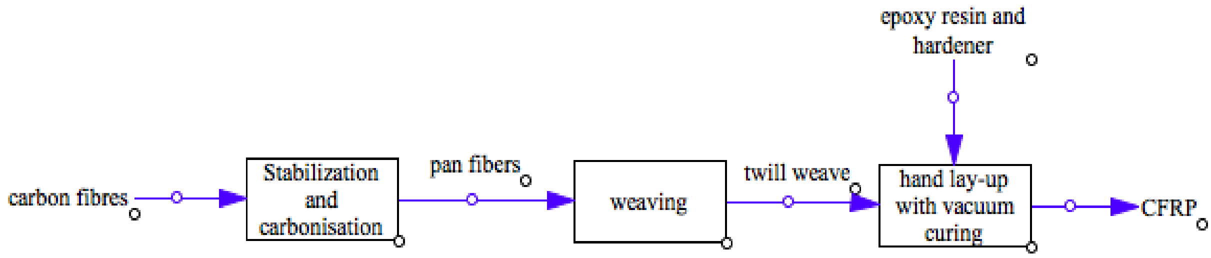

Figure 8: CFRP production

It is assumed that aramide has the same environmental impacts as CFRP because no more detailed information about aramid is available; therefore the weight of aramide is added to the weight of CFRP. CFRP has a share of 27.94% in the thyssenkrupp SunRiser with 100.71 kg. In the thyssenkrupp blue.cruiser are 111 kg of CFRP plugged. (see Table 1: ABC analysis SunRiser weight and Table 2: ABC analysis blue.cruiser weight). In addition, 3.69 kg of glass fibres and the blend are added. The share in the blue.cruiser is 32.80%[51]. The same offcut is also assumed for the SunRiser. In the SolarCar CFRP is used for the exterior automotive trim and in the thyssenkrupp sunriser it is also used for the interior trim.
Usually CFRP residues are deposited because CFRP is unestablished in the mass market. Therefore the development for the recycling technologies for residues of CFRP is still in the beginnings. Because of the slight mass, the material is usually shredded and blended with other products like e.g. sheet moulding compounds (down cycling)[52]. HADEG, a recycling firm, investigates thermal processes to recover the carbon fibres by simultaneously using the heating value of the resins in a pyrolytic process. In this process the material is sorted and shredded in order to be heated in the pyrolysis process to 400 - 1000 degrees Celsius so that the matrix material evaporates. The process occurs under inert gas because the fibres must not contact with oxygen[53]. The process is energy efficient, and emission reducing, because recove energy, and solar energy is used[54]. For modelling, the preciously accepted scenario of down-cycling is assumed, in which CFRP is first pelletized and then reused.

[50] Cf. Sebastian Nöll 2010
[51] (85,579 kg -70,447 kg) : 85,579 kg)
[52] Cf. Matthias Achternbosch 2002, 8
[53] Cf.Jens Wieberneit 2015, 25
[54] Cf. Dr. Heinz Eickenbusch, Dr. Oliver Krauss 2013, 32

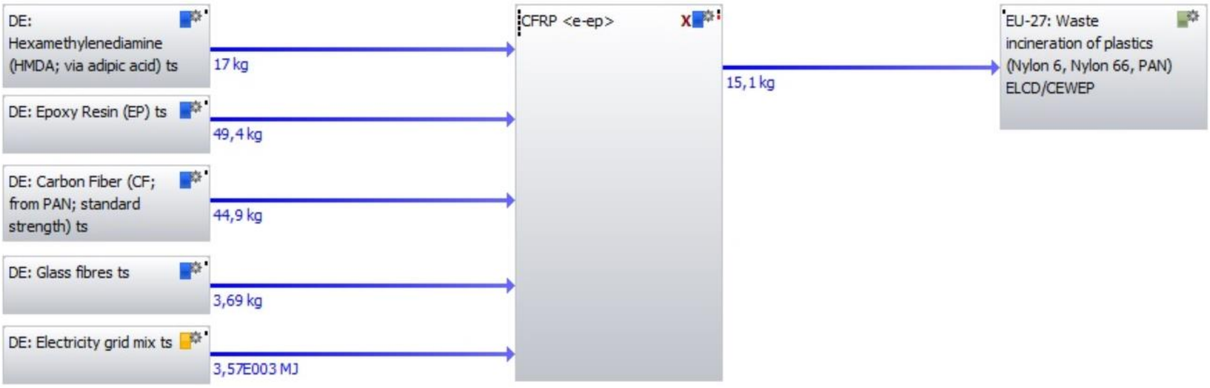

Figure 9: CFRP flowchart in GaBi

3.2.4 Natural fibre reinforced plastic

Natural fibres a reinforced plastic is a material made of a synthetic substance mixed with natural fibres to achieve more stability, strength and sparseness. NFRP is resilient but also lightweight; additional to that it shows good acoustic and damping characteristic[55].

Another benefit of NFRP, especially in the automotive industry is its property to splinter less than other materials e.g. CFRP. NFRP has also economically and ecologically advantages[56]. It does not depend on the oil price and it is mostly made from renewable raw materials[57].

NFRP are implemented in the interior of the SolarCar, components like the dashboard, the inner doors or other cladding components are produced with NFRP. Just like steel, it occurs as a substitution material for CFRP which was dominating material used for the interior of the predecessor. Due to its weight and meaning as a substitute material, it is considered as a hotspot. NFRP is a mix of natural fibres and synthetics. Natural fibres can be divided into three main groups: vegetable fibres e.g. flax or hemp, animal fibres e.g. wool to other animal hair or mineral fibres.

In the industry only natural fibres, made of vegetable fibres are used, because of their mechanic characteristics, as well as in the SolarCar, where natural fibres out of flax were used.

The used NFRP in the SolarCar is hand laminated and consists of a resin and hardener, with an increased quantity of content from plant and vegetable origins mixed with flax fibres[58]. In the thyssenkrupp blue.cruiser, 12.4 kg are installed (see Table 2: ABC analysis blue.cruiser weight).

It is possible to recycle the fibre and reuse them, but hand in hand with that goes a loss of quality. If the NFRP is not reused, it will be thermally combusted.

The entire flow chart of NFRP in GaBi can be seen in the following Figure 10: NFRP flowchart in GaBi.

[55] Cf. Fachagentur Nachwachsende Rohstoffe e. V.
[56] Cf. ZEIT ONLINE GmbH 2012
[57] Cf. Michael Karus 2006
[58] Cf. Sicomin Epoxy Systems 2014

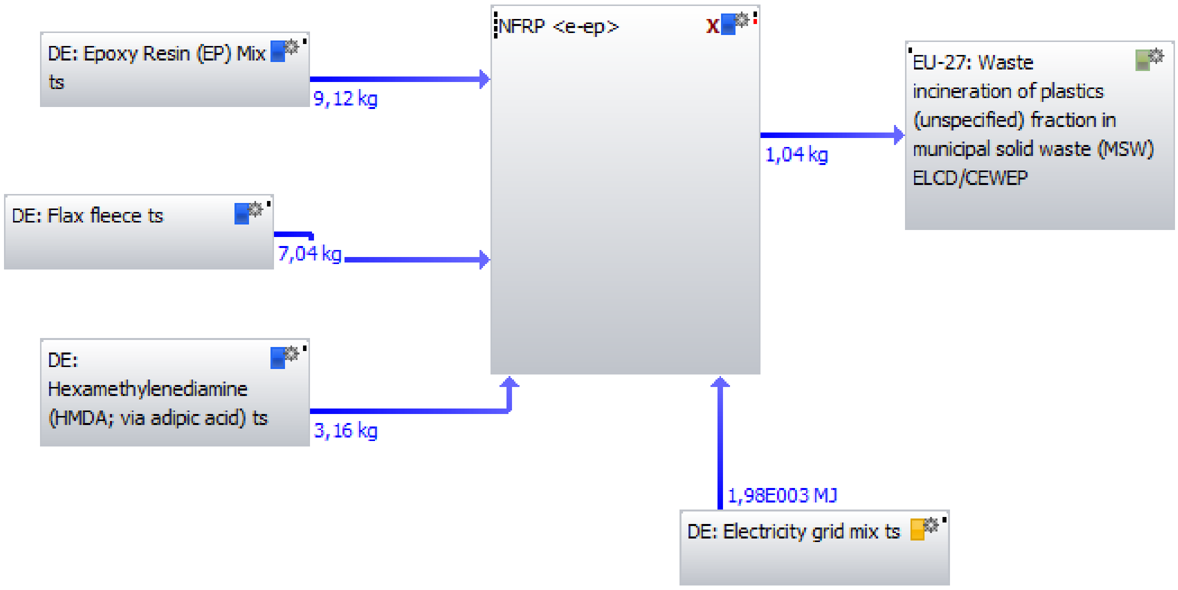

Figure 10: NFRP flowchart in GaBi

3.2.5 Steel

Steel is an alloy of iron, with a reduced carbon content (2%)[59], by alloying other materials, various properties can be applied.

The steel which is used in the SolarCar is mostly from thyssenkrupp Steel Europe. There are several forms of steel installed in the SolarCar like the complex phase steel CP-W and CP-K for components like chassis, crossbeams and reinforcements for the body or the B-pillar. There are two types of electrical sheet used in the SolarCar, the thyssenkrupp PowerCore C 120-30 and the thyssenkrupp PowerCore NO20-280-30AP.

Components made of steel are mainly installed in the body, in some parts of the interior and in other smaller parts of the SolarCar.

It is a substitute material for CFRP, which was mostly used in the predecessor. Although steel is heavier than CFRP, it is a logic alternative because of its environmental effects in the production process and recycling process. To determine which materials are considered as a hotspot an ABC-Analysis was created. The Materials were categorized by weight or negative environmental effects.

[59] CHEMIE.DE Information Service GmbH

In total, 33.21 kg in the SunRiser and 101.5 kg in the blue.cruiser have been installed (see Table 1: ABC analysis SunRiser weight and Table 2: ABC analysis blue.cruiser weight)

Figure 11: Steel production gives an overview of steel production. Starting material for steel is pig iron, which is mostly made of iron ore with a high proportion of iron and other materials such as coke and scrap[60].
The properties of steel can vary; it depends on the materials, which are added in the production. Some of the most common properties are hardness, corrosion resistance or formability. Nowadays there are several ways of further processing the steel sheet. The two most common procedures are the production in a blast furnace and the production in with electric arc furnace.

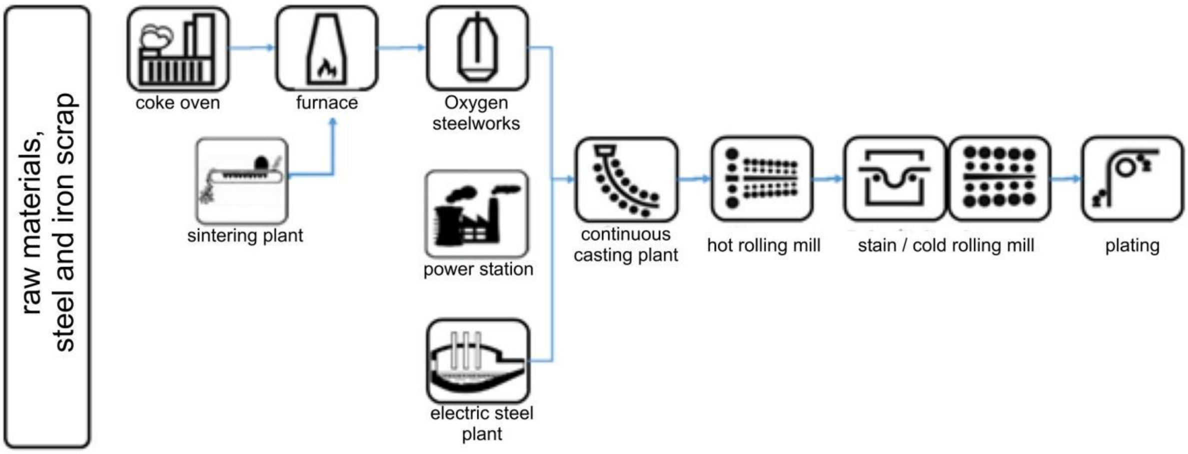

Figure 11: Steel production

In the blast furnace the unwanted substances like carbon are separated from the iron ore by oxidation through a lance, which blows oxygen on the pig iron and which is then further processed in converter and pans.
The electric arc furnace works with electrical energy to melt steel scrap and iron ore mixed with alloy. Where the blast furnace route is primary steel making (scrap input 10 – 20%) and the EAF route is secondary steel making (scrap input ~ 90%).
Steel is completely recyclable[61]. Also it by-products occurring during the production, such as slag, can be used as fertilizer, for the cement production or for the construction industry.
It is a form of closed-loop recycling. All the materials especially the scrap iron is used again without a loss of quality. The entire modelling of steel in GaBi is shown in Figure 12: Steel flowchart in GaBi.

[60] Cf. Wirtschaftsvereinigung Stahl
[61] Cf. Andreas Theuer 2016

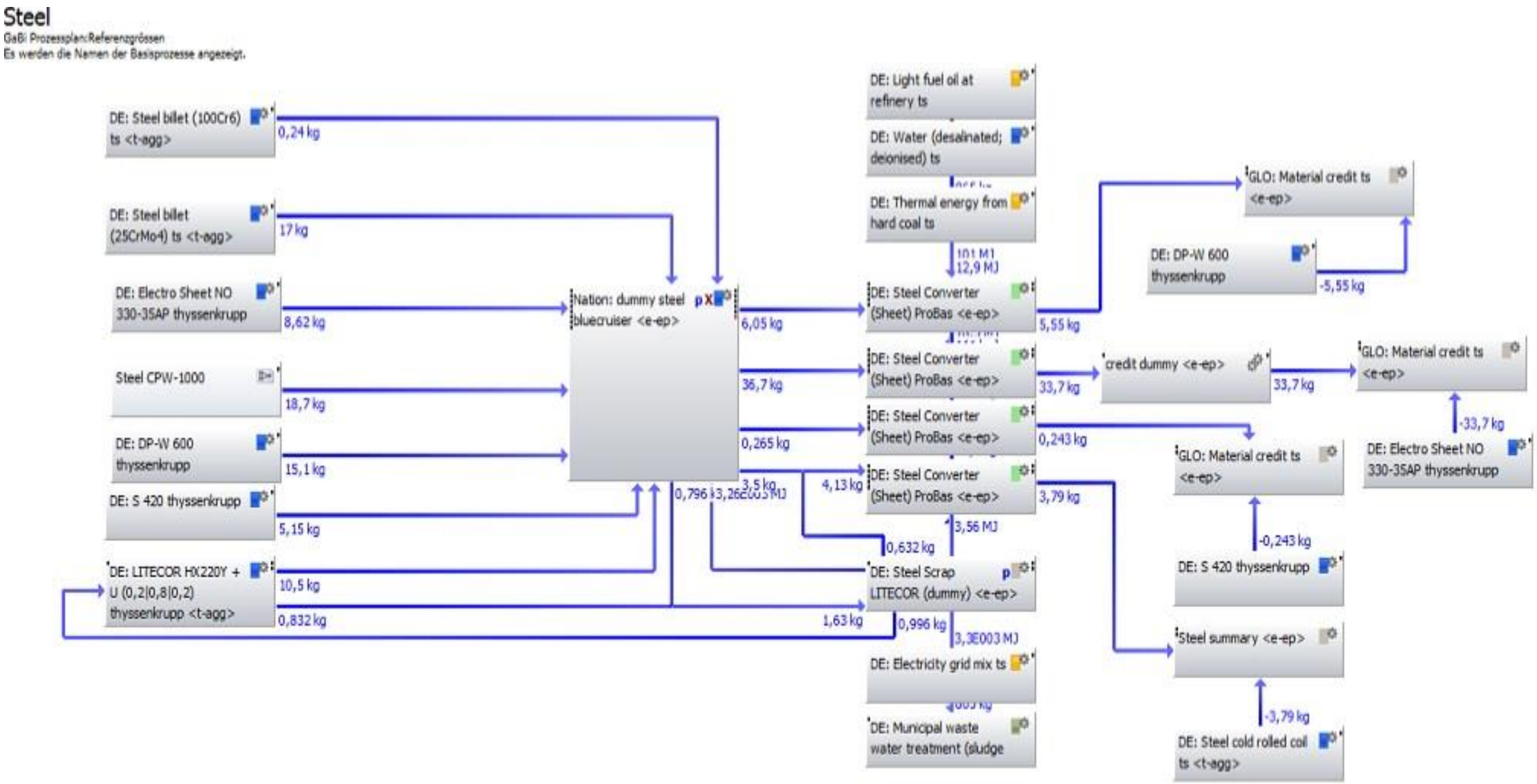

Figure 12: Steel flowchart in GaBi

3.2.6 ROHACELL®

ROHACELL® is a structural foam, formed based on polymethacrylimide. It is a product of Evonik. ROHACELL® IG-F is used for the thyssenkrupp SunRiser and the thyssenkrupp blue.cruiser. It is available in plate form in various designs. It serves as a core material in the SolarCar between the carbon and aramide layers.
The main reason, to decide that ROHACELL® occurs as a hotspot, is the fact that is not recyclable.

Polymethacrylimide is composed of methacrylic acid and acetonitrile. To produce 1 kg of ROHACELL® 116.149 g of acetonitrile and 974.5 g of methacrylic acid are needed. Polymethacrylimide is a polymer made of hard plastic and hard foam. It is usually serves as a sandwich construction between two cover layers made of solid plastics. These materials have high thermal resistance for plastics. The basis of polymethacrylimide is formed by foaming at 170 to 220 degrees by the above-mentioned substances. Methacrylate is an unsaturated carboxylic acid, a so-called alkenoic acid. It serves as a starting material to produce plastics[62].
It is industrially produced from isobutylene and tert-butanol, which are first oxidized to methacrolein and then oxidized to methylmethacrylate. Synthetically, it can also be prepared by hydrolysis and acetone cyanohydrin and subsequent water cleavage[63]. Evonik's Website has some information about stability and reactivity. The thermal decomposition starts at > 350°C[64].

The plates are characterized by high stiffness and compressive strength as well as low heat and cold contraction and are therefore well suited for use as core material in the SolarCar. ROHACELL® is required for the reinforcement of CFRP components, so that the desired stiffness can be achieved.
The totally weight of ROHACELL® in the thyssenkrupp SunRiser is 13.57 kg. That's 3.77% of the overall weight. The thyssenkrupp blue.cruiser has a totally weight of 8.08 kg ROHACELL® in the car. It is not as much as in the thyssenkrupp SunRiser anymore and only 1.73% of the overall weight. (see Table 1: ABC analysis SunRiser weight and Table 2: ABC analysis blue.cruiser weight).

As mentioned above ROHACELL® cannot be recycled. That's why it must either be disposed of thermally by incineration or by land filling[65]. In view of the fact that it is a non-renewable raw material, it is therefore to be considered critically.
The entire modelling of ROHACELL® in GaBi is shown in Figure 13: ROHACELL flowchart in GaBi.

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[62] Cf. National Center for Biotechnology Information
[63] Cf. Biederbick 1983
[64] Cf. Evonik Resource Efficiency GmbH 2015
[65] Cf. Evonik Resource Efficiency GmbH

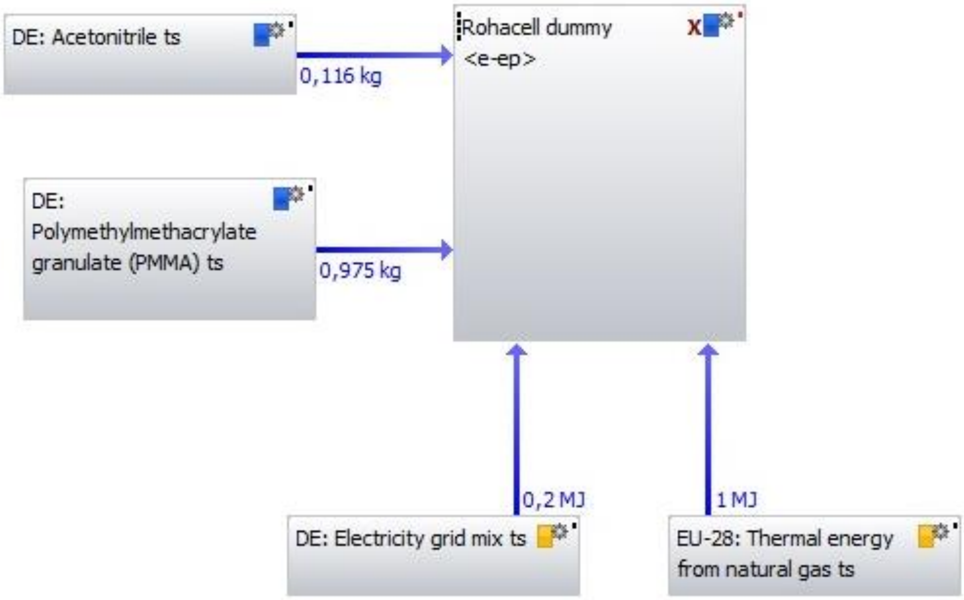


Figure 13: ROHACELL flowchart in GaBi

3.2.7 Aluminium alloy

In the SunRiser and the blue.cruiser an aluminium alloy is used. The alloy is named En Aw-7075T6 or Al Zn5,5 MgCu[66].

The form is a hardening wrought alloy of the group AlZnMg. Main components of the alloy, shown in Table 7: Elements of the aluminum alloy, are aluminium (91.42 %), zinc (5.1 %), magnesium (2.1 %), copper (1.2 %) and chrome (0.18 %) There are small amounts of aluminium alloy in the doors and the seat console of the thyssenkrupp SunRiser. In addition, the front and the rear chassis as well as the steering wheel exist of aluminium alloy parts. Furthermore, there is aluminium alloy in the holder “Domstrebenhalter” and the rim. In total, there are 25.98 kg of aluminium alloy in the SolarCar SunRiser. In the thyssenkrupp blue.cruiser 36.70 kg of the aluminium alloy are used[67]. Mainly the aluminium alloy is used for the steering wheel and the front and rear chassis. Furthermore, there is aluminium alloy in the engine and the brake of the thyssenkrupp blue.cruiser[68].

[66] Herrmann-buntemetall
[67] SolarCar Mechanics-Team
[68] SolarCar Mechanics-Team

Table 7: Elements of the aluminum alloy[69]

Elements	Percentage	Actual weight
Aluminium	91.42 %	13.96 kg
Zinc	5.1 %	0.779 kg
Magnesium	2.1 %	0.321 kg
Copper	1.2 %	0.183 kg
Chrome	0.18 %	0.027 kg
Total	100 %	15.27 kg

Aluminium is one of the hotspots in this LCA because it has a weight share of over 7 % inthe thyssenkrupp SunRiser and the thyssenkrupp blue.cruiser. In total these are 25.98 kg (see Table 1: ABC analysis SunRiser weight and Table 2: ABC analysis blue.cruiser weight) aluminium alloy in the SunRiser and 36.70 kg in the blue.cruiser. In addition, aluminium plays a role in the category of environmental relevance. One reason is the not ecologically acceptable production of aluminium. To produce primary aluminium a high value of energy is required. For instance, at the molten-salt electrolysis an amount of 13-18 kWh energy per kilogram aluminium is needed[70]. In comparison, to produce steel an amount of 5.6 kWh energy per kilogram is needed[71]. Furthermore, to produce one-kilogram primary aluminium, four times the amount of bauxite is necessary. That shows the claim of nature space is very high. A by-product at the production of aluminium is carbon dioxide. For one-kilogram aluminium 9.7 kg carbon dioxide equivalent are produced. In addition, the red sludge needs to be disposed on a dump. Through the caustic soda in the red sludge, the sludge needs to be stored in such a way, that no components can reach the ground and the ground water. Per one-kilogram of aluminium 0.7 kg of red sludge are produced[72].

To produce aluminium, the ore bauxite, which is with eight percent the third-most frequent element of the earth's crust, is necessary. The production of aluminium requires two steps. At first, the alumina is separated from the bauxite with the "bayer process". Therefore, the ore is set in caustic soda and all foreign matters are removed under stirring with high pressure and aluminium oxide (Al_2O_3) is burnt. Next to aluminium oxide, also red sludge is produced as a by-product, which is, because of the caustic soda inside, endangering the environment.[73] In the second step, the aluminium is won through the molten-salt electrolysis ("Hall-Héroult-Process"). At this process, aluminium is produced at the cathode on the ground whereas oxygen is produced at the anode. The oxygen reacts with graphite to carbon dioxide. The educated aluminium on the ground is taken away in the last step by a pipe (see Figure 14: Aluminium alloy production).

[69] SolarCar Team
[70] Cf. Matthias Dienhart, 6
[71] Cf. FIZ Karlsruhe – Leibniz-Institut für Informationsinfrastruktur GmbH 2006
[72] Cf. Muster 2007, 7
[73] Cf. Rudolf Vetsch 2016

Non hardenable alloys receive their strength through cold machining by pulling or rolling. Hardenable alloys get their strength through heat machining in three steps: The solution annealing (500°C), quenching and outsourcing[74].
Aluminium alloy has some qualities, which are important for the SolarCar. Through the combination of magnesium and zinc, it is possible to reach (up to now) the highest strength in aluminium alloys. It also has good material fatigue quality. Copper as another addition in the alloy further improves the firmness and counteracts against the stress corrosion cracking[75]. The low density is a sign that the aluminium alloy has the character of a light metal[76]. All of it is important for vehicles and efficient mobility. The mobility is also ecologically friendly in its phase of utilization. To improve the ecological compatibility, it obviously requires using secondary aluminium instead of primary aluminium. Aluminium scraps are melted down to produce the secondary aluminium. The secondary aluminium has the same quality as the primary aluminium. The use of aluminium scrap metal would prevent the origin of other red sludge and would not claim other nature space so the pollution of the environment is less.

For the aluminium alloy recycling it is important to separate the elements of the alloy according to their type. If there is a correctly sorted scrap of aluminium alloy, it is possible to recycle the alloy. 100 % of the aluminium alloy scrap could be led back in the material circulation. If the elements of the alloy are mixed (not separated by type), it comes to down cycling[77].

More than 70 % of the produced aluminium until now is still in use. This shows the durability of the metal. 100 % of the aluminium scrap could be led back in the material circulation. Furthermore, aluminium is a very good metal to recycle because it is possible to use 95% less energy to produce secondary aluminium. This means that only 0.7 kWh per kilogram are necessary for the secondary aluminium production[78].

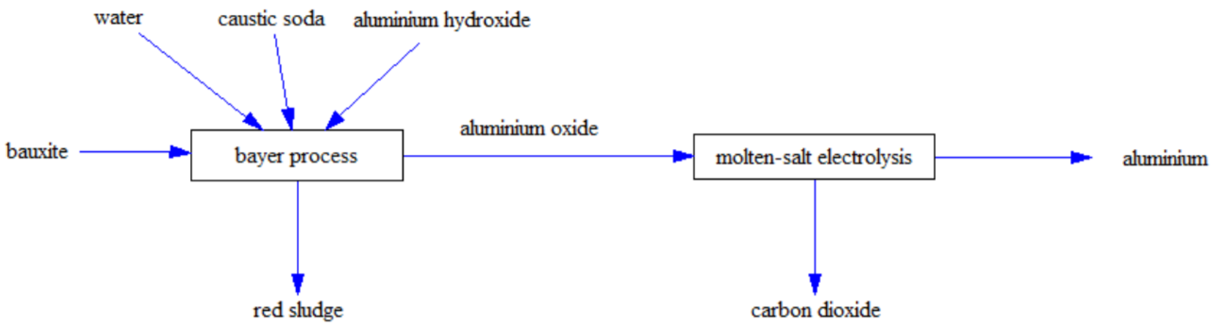


Figure 14: Aluminium alloy production

[74] Cf. Rudolf Vetsch 2016
[75] Cf. Rudolf Vetsch 2016
[76] Cf. Herrmann-buntemetall
[77] Cf. Rudolf Vetsch 2016
[78] Cf. Rudolf Vetsch 2016

3.2.8 Lithium ion battery

The lithium-ion battery for the thyssenkrupp SunRiser, as well as for the thyssenkrupp blue.cruiser, is assembled by the SolarCar Team itself. It consists of four main components, namely the battery cells, the battery housing, the battery management system (in short BMS) and the cooling system. These components are further divided into more subsystems[79].

The battery built into the thyssenkrupp Sunriser has an energy content of 14.8 kWh, while the one in the thyssenkrupp blue.cruiser reaches an energy content of 14.6 kWh. With an average speed of 60 km/h a fully charged battery lasts for ~800 km (without sun power).

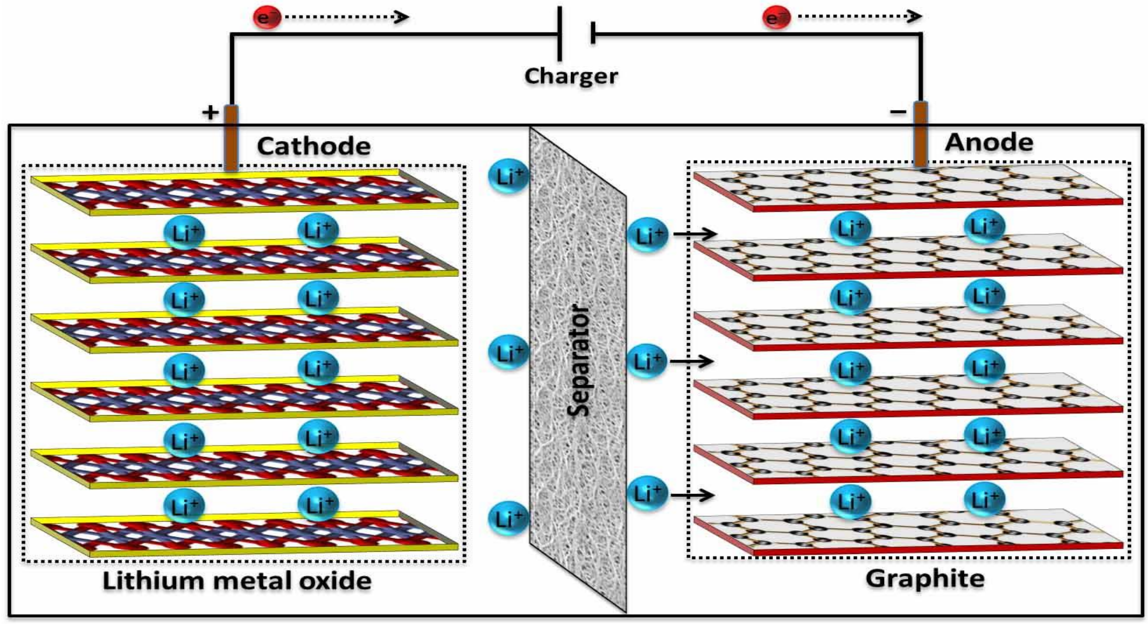


Figure 15: Functionality of a Lithium-ion battery cell[80]

As seen in Figure 15 when the battery cell is in use a few abundant Lithium-ions break away from the positive electrode (or cathode) made up of a Lithium metal oxide and gravitate because of a surplus of electrons through a polyolefinic separator to the negative electrode (or anode) made from graphite. Both electrodes are surrounded by an electrolyte based on Lithium hexafluorophosphate ($LiPF_6$) and many sol-vents[81].

Before a battery cell like the NCR18650, which is produced by Panasonic and used in both SolarCars, can be titled as a finished product, it must undergo an array of processes. Figure 16: Lithium-ion battery production shows a simplified depiction of these processes.

[79] Cf. Ellingsen *et al.* 2014, 113–114
[80] Cf. ViPER Group n.d
[81] Cf. Korthauer 2013, 23

First the cathode's active material, in this case Lithium nickel cobalt aluminium oxide ($LiNiCoAlO_2$) or short NCA[82], the binder Polyvinylidene fluoride (PVDF), the conductive additive carbon black and the solvent N-Methyl-2-pyrrolidone (NMP) are mixed together to create the positive cathode paste.[83] In the next step this paste is applied to the aluminium current collector and subsequently dried in the oven. Through the drying of the paste the solvent evaporates. Afterwards the cathode is compressed for thickness control and cut to size. For the anode, the processes are the same, but instead of $LiNiCoAlO_2$ the active material is graphite[84], less binder is used, and the conductive additive is omitted[85]. The separator is manufactured by coating a porous polyethylene film with a paste composed of a copolymer, Dibutyl phthalate ($C_{16}H_{22}O_4$) and Silicon dioxide (SiO_2) dissolved in acetone (C_3H_6O) and drying it through heating to leave a porous film[86]. Once the separator and both electrodes are wound together cylindrically and wrapped within a Polypropylene (PP) resin pouch, they are inserted into a thin aluminium casing. Afterwards the casing is filled with an electrolyte consisting of the salt $LiPF_6$ and the solvents Ethylene carbonate ($C_3H_4O_3$), or short EC, and DEC, short for Diethyl carbonate ($C_5H_{10}O_3$)[87]. At the end, the case is sealed and the battery cell is charged by using a cycler before it gets tested for its functionality (see Figure 16: Lithium-ion battery production)[88].

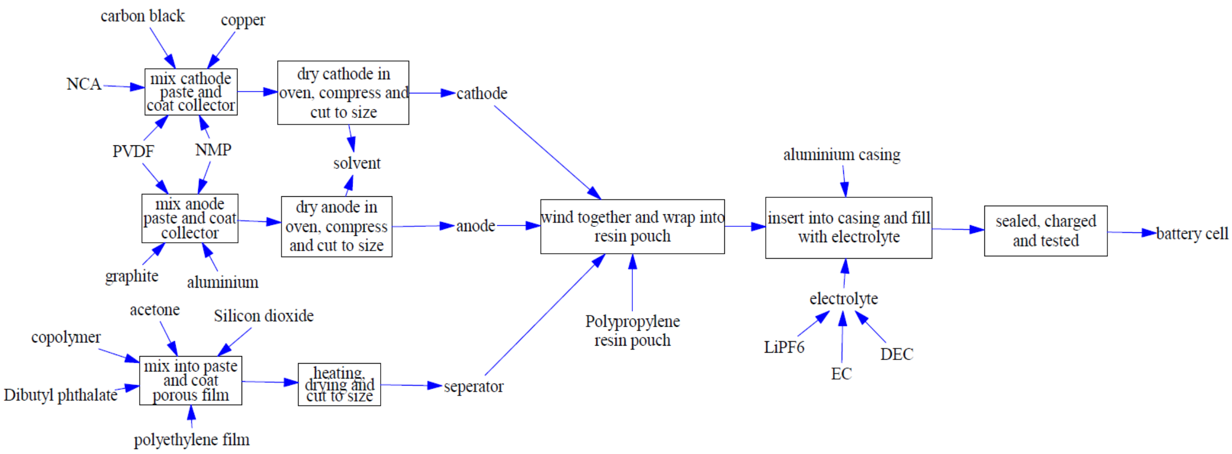


Figure 16: Lithium-ion battery production

The individual battery cells are being connected through a connecting plate made from Nickel to form 36 different modules made of 37 battery cells each. These modules are laid out into the battery packaging in three rows separated through a separator made from Polystone® M (PE-UHMW). The two separators to detach the modules from the battery housing wall are made from Polyethylene[89].

[82] Panasonic Industrial Company 2015
[83] Cf. Korthauer 2013, 23
[84] Cf. Panasonic Industrial Company 2015
[85] Cf. Ellingsen *et al.* 2014, 115
[86] Cf. Notter *et al.* 2010, 6552
[87] Panasonic Industrial Company 2015
[88] Cf. Amarakoon *et al.* 2013, 41–43
[89] SolarCar Battery-Team

The battery housing itself is made from CFRP and GFRP (glass fibre reinforced plastic) with a core of ROHACELL® and has an insulating layer made from cork[90].

The cooling system of the Lithium-ion battery consist of two different types of DC/DC-converter, two different types of heat sinks and two printed circuit boards.
The heat sinks HAQ-10T and HAH-15T, both manufactured by TDK-Lambda and installed in a one to three ratio into the thyssenkrupp blue.cruiser, are made out of aluminium. The DC/DC-converter CN50A110 and CN20A110, installed in a one to three ratio as well, are also manufactured by TDK-Lambda[91].

The BMS is composed of a multitude of electrical parts. Next to an array of different wirings and fuses there are also two gas sensors to detect dangerous gases early on, three instrument shunts, four contactors and two DC/DC – radiator fans. Finally, all previously described components are assembled to form the battery pack. It is then placed into the vehicle in a retainer made from CFRP[92] and secured with four blocking pins of the type 03089 – 18105, produced by norelem[93] and made of stainless steel[94, 95].

A shortened flow chart of the different production steps using the example of the thyssenkrupp blue.cruiser can be seen in Figure 17 Lithium-ion battery flowchart in GaBi.

The Lithium-ion battery used in the thyssenkrupp SunRiser had a total weight of 87.1 kilogram, while the new battery for the thyssenkrupp blue.cruiser weights 99.57 kilogram. Due to the afore mentioned usage scenario, each SolarCar needs one battery throughout its lifespan. As a result, the battery contributes at a high ratio to both, the gross vehicle weight, and the cumulated carbon dioxide equivalent of the SolarCars. Therefore, the Lithium-Ion battery can be categorized as an A-product, as can be seen in Table 1: ABC analysis SunRiser weight and Table 2: ABC analysis blue.cruiser weight.
The battery is located under the bonnet of the SolarCar and is directly connected to the solar cells and the engine of the vehicle.

[90] SolarCar Battery-Team
[91] SolarCar Battery-Team
[92] SolarCar Battery-Team
[93] For further information: www.norelem.de
[94] Cf. norelem Normelemente KG n.d
[95] Cf. Amarakoon *et al.* 2013

LithoRec II was a project fostered by the Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit and conducted under the coordination of the Rockwood Lithium GmbH and its associates from summer 2012 through fall 2015. This process conduces the recovery of lithium, cobalt and further materials used in battery cells, and are subdivided into the following process steps: dismantlement of the battery and its module, dismantlement of the individual battery cell and separation of the active material, and hydrometallurgical processing of the active material[96].

First the whole battery is being exhausted and dismantled into its individual components, such as the battery cells, the battery housing, the cooling system and the BMS. These components are recycled directly, while the battery cells are brought to the next processing step. Here the battery cells are being shredded before solvents and the majority of compounds containing fluorine are extracted by using Dimethyl carbonate (DMC). The refined product is dried in an oven before aluminium and steel components are separated from the material. After further shredding the remaining material is elutriated and thus divided into heavier and lighter elements. The heavier materials consist mostly of copper and aluminium and can be recycled directly, while the lighter materials need to be filtered and cleaned with water. As a result, the separator and elements containing fluorine are separated from the active material. As a last step, the active material is processed hydrometallurgically. First other components, like carbon black, are separated, and then elements like cobalt and nickel are dissevered through a sulphate solution. Finally, the lithium is purified obtained as lithium hydroxide[97]. The entire model of the battery is shown in Figure 17 Lithium-ion battery flowchart in GaBi.

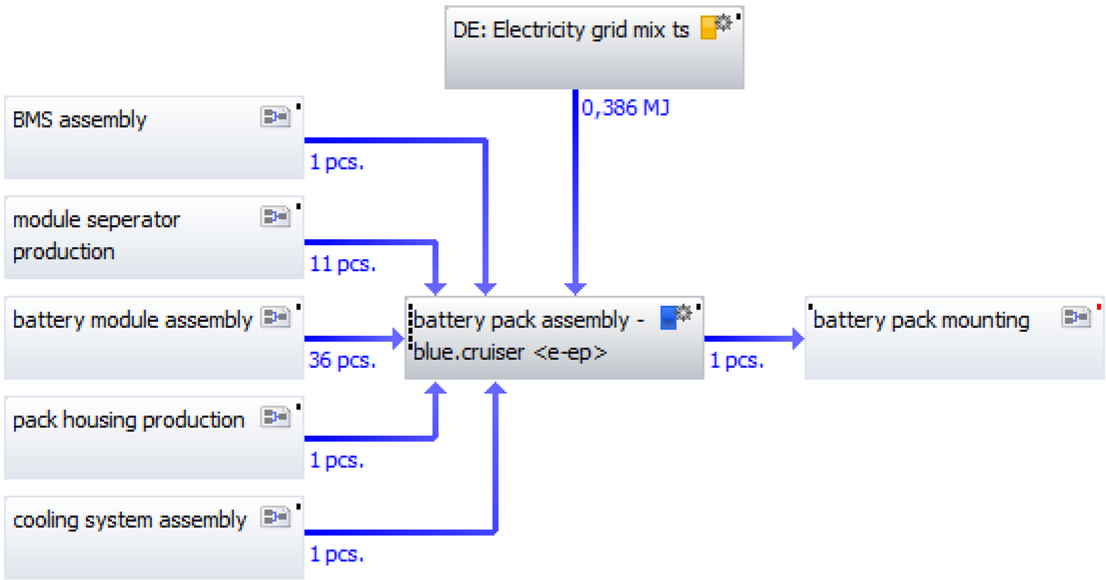


Figure 17 Lithium-ion battery flowchart in GaBi

[96] Cf. Matthias Buchert/Jürgen Sutter 2015, 5–6
[97] Cf. Buchert/Sutter 2015, 19–20

3.2.9 Silicon solar cell

For the thyssenkrupp blue.cruiser a silicon solar cell was used to replace the harmful triple junction GaAs cell. The MAXEON™ GEN III cell of sunpower is monocrystalline and has a cell thickness of 165µm +/- 40µm. The solar cell efficiency is 23.4%[98]. The data for inputs and outputs were taken by ProBas and are derived from a monocrystalline solar cell with an efficiency of 14% (it is assumed that the environmental impacts of the production and the recycling are similar)[99].

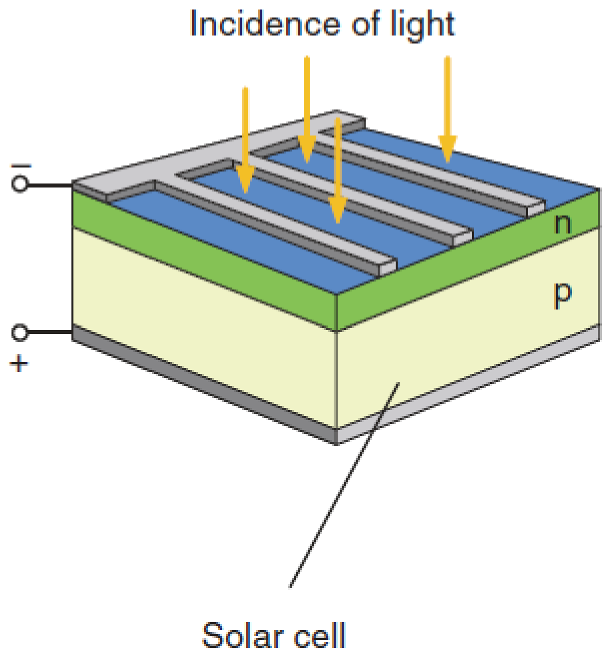


Figure 18: Structure of a solar cell[100]

As seen in Figure 18 the silicon solar cell consists of different layers, which are generally bound together by a negative and a positive electrode. The MAXEON™ GEN III solar cell however uses a metal grid only on the back of the cell to further its degree of efficiency[101]. To improve the conductivity of the silicon, foreign atoms are added through doping. One layer of the silicon solar cell is furnished with phosphor while the other is furnished with boron. In the n-type layer, which is the phosphor layer, an excess of negatively charged electrons arises. In the p-layer, the boron layer, holes are formed in the charge structure, which serve to transport the electric charge. Due to the different doping, a boundary layer is formed in between the n-type and the p-type layer and thus creating two electrically charged regions and with them an electric field[102]. If sunlight hits the solar cell, the electrons are getting induced and an electron-hole pair is formed. The electric field prevents the resulting charge carriers from recombining and pulls them apart to the surface of the layers, where they can

[98] Cf. SunPower Corporation 2015
[99] Nowak 2012
[100] Cf. Mertens 2014, 13
[101] Cf. SunPower 2015
[102] Cf. Mirja Beste 2016

be tapped as photocurrent[103]. To obtain as much energy as possible, an antireflection coating is applied.

Silicon is obtained from quartz sand, also known as raw silicon or silicon dioxide. First the metallic silicon is crystallized from the molten mass of liquid trichlorosilane in a melting process with temperatures higher than 1400°C. To obtain monocrystalline silicon, a crystal rod, which exhibits a crystal lattice, is drawn from the molten mass. Black 0.4 mm thick slices are sawn from the bars which are called wafers[104].
These wafers are, as previously stated, furnished with boron. They are cleaned in hydrogen chloride to remove any residual from the production and hydrofluoric acid to remove oxidation on the wafer. After drying the wafer in an oven, the already doped wafer is furnished with phosphor through thermal diffusion. In the oven, the wafer is surrounded by Phosphoryl chloride ($POCl_3$) and oxygen. These gases interact and phosphor silica glass precipitates on the wafer. As a result, phosphor atoms diffuse into the wafer and create the n-type layer of the silicon cell. The residual phosphor silica glass is removed by cleaning the wafer in hydrofluoric acid. Afterwards a thin antireflective coating is sprayed onto the wafer and the tin-coated copper metal grain is silk-screened onto the back of the wafer[105].
Figure 19: Silicon solar cell flowchart in GaBi shows a flowchart with every material that is built into the Silicon solar cell.

The silicon solar cell is analysed in this study to create a comparison to the triple junction GaAs solar cell, which substitutes for. As the world's first solar company to earn the Cradle to Cradle Certified™ Silver designation, SunPower ensures the Recycling of its direct current panels, which are manufactured in Mexico, France and the Philippines. A possible process to recycle solar panels is the pyrolysis. During this process of thermochemical elimination, process temperatures up to 600°C are used under the exclusion of oxygen. In this process glass and plastics are separated from the silicon-semiconductor. Afterwards the solid matter is extracted from the metal-containing liquid through a pH-precipitation. After an array of further chemical processes the precipitated material can be filtered, pressed and utilised for a new solar cell[106].

[103] Cf. Frieder Braun 2012a
[104] Cf. Mirja Beste 2016
[105] Frieder Braun 2012b
[106] Cf. Robert Doelling 2013

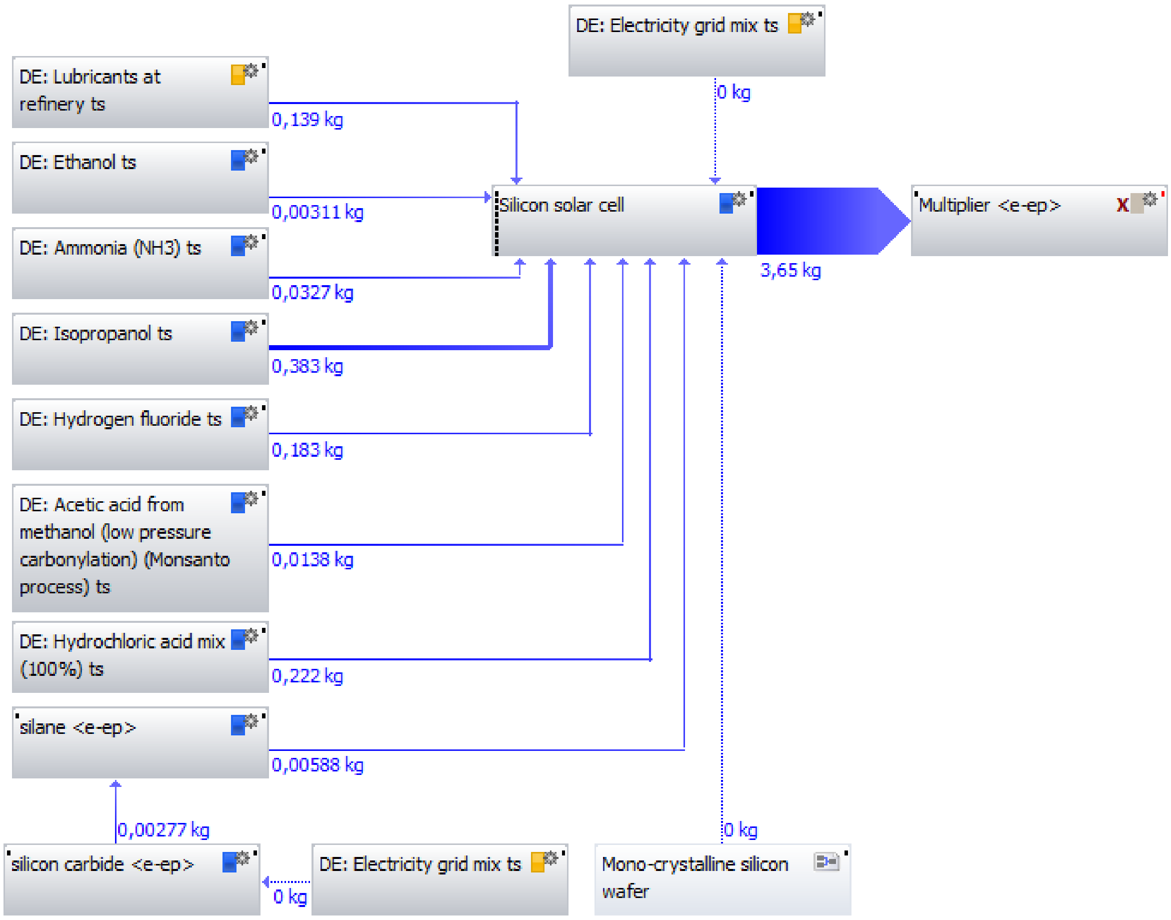


Figure 19: Silicon solar cell flowchart in GaBi

3.2.10 Triple Junction solar cell

The Triple Junction GaAs Solar Cell – Type: TJ Solar Cell 3G30C produced by AZUR SPACE SOLAR POWER GMBH is used for the SolarCar thyssenkrupp SunRiser. Triple junction solar cells are used in spacecraft and satellites[107].

There are no LCAs of triple junction solar cells production found and no information about the recycling neither. Main reason might be that 95% of the world wide used solar cells are silicon solar cells[108]. For this reason, the model of silicon cell which is used for thyssenkrupp SunRiser is used as basis for Triple Junction GaAS Solar Cell as well. The material silicon is replaced with the materials from Triple Junction GaAS Solar Cell. The materials are silver which is in GaBi software, arsenic and gallium which are found in ProBas database and germanium. For germanium results from another LCA were used[109]. Gallium is produced as a by-product of aluminum, indium is produced as a by-product of zinc and arsenic is produced via arsenic trioxide as a by-product of copper[110]. Gallium Arsenide is a toxic material. The end of life scenario of the silicon solar cells could not be used for GaAS solar cell because a database

[107] Cf. Jennifer E. Granata
[108] Cf. Jennifer E. Granata
[109] Cf. Nuss P 2014
[110] Cf. N. J. Mohr, J. J. Schermer, M. A. J. Huijbregts, A. Meijer, L. Reijnders 2007

from ProBas is used. That is the reason why the materials cannot be replaced. For this reason, the GaAS solar cell is land filled in the model.

Because of the difficult data management there is no flow chart constructed. The information is from LCA studies "*Life cycle assessment of Thinfilm GaAs and GaölP / GaAs solar modules*"[111] and one of single junction GaAS solar cell[112], which can be used for general information of the materials.
A triple junction cell is also called multi junction cell. The main functionality is to absorb different wavelengths by different materials. The top of the cell (GaInP) absorbs the short wavelength (blue spectrum of the light) the middle cell (GaAs) absorbs the green spectrum of the light and the bottom cell (Ge) absorbs the red spectrum of the light. The cell design is shown in Figure 20. The absorption of the different wavelengths effects greater efficiency. "*Data show that triple-junction solar cells provide more power than any previously available cell technology, including dual-junction*"[113] The efficiency of the used triple junction solar cells is 29.2 %. The triple junction solar cells are located on the surface of the thyssenkrupp SunRiser. They transform the sunlight into electric energy which drives the motor.

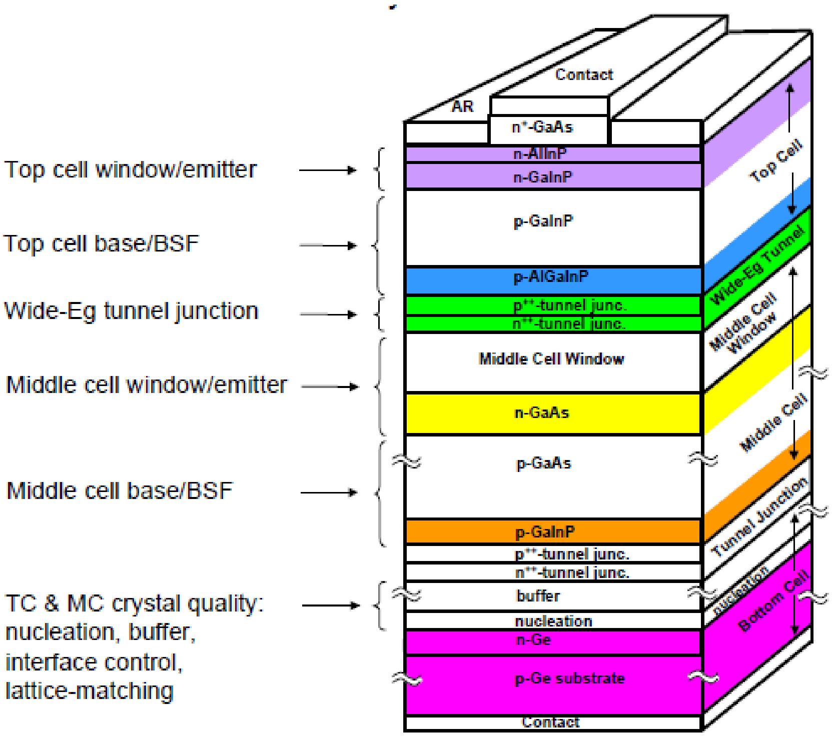


Figure 20: Cross section of a triple junction solar cell

As you can see in the data sheet[114], main materials are Indium gallium phosphide (GaInP), gallium arsenide (GaAs) and germanium (Ge) (see Table 8: Constituent parts of Triple Junction Solar Cell). As the SolarCar team says there are contained other materials as well which are not mentioned in the data sheet. The weights were estimated by SolarCar Team of Bochum University of Applied Sciences. If you use

[111] Cf. N. J. Mohr, J. J. Schermer, M. A. J. Huijbregts, A. Meijer, L. Reijnders 2007
[112] Cf. Gladden *et al.* 2012
[113] Cf. R. R. King 2000
[114] AZUR SPACE Solar Power GmbH 2016

the regular cut-off criteria (see 2.2 Scope) we could resign to mode arsenic, indium gallium phosphide, aluminium, aluminium mixed oxide and titan mixed oxide. Because the materials GaAs and GaInP are mentioned in the data sheet as two of three materials they are not cutted of. With the weight of 10 kg, the solar cells are a B-Product in the method of ABC-analysis by weight (see in Table 1: ABC analysis SunRiser weight and Table 2: ABC analysis blue.cruiser weight). But the environmental impact of CO_2 equivalents makes the Triple Junction Solar Cell to an A-Product of ABC-analysis by CO_2 equivalents (see Table 3: ABC analysis SunRiser CO2-eq. and Table 4: ABC analysis blue.cruiser CO2-eq.) and therefore it is selected as a hotspot for this LCA.

Table 8: Constituent parts of Triple Junction Solar Cell

Material	Percentage [%]	Weight [kg]
Gallium	1.6	0.16
Arsenic	0.9	0.09
Silver	8.0	0.80
Gallium indium phosphide	0.8	0.08
Germanium	88.0	8.80
Aluminium	0.1	0.01
Aluminium mixed oxide	0.3	0.03
Titanium mixed oxide	0.3	0.03

3.2.11 Magnesium alloy

A Magnesium alloy was used in the thyssenkrupp SunRiser, but not in the blue.cruiser. The Alloy named Magnesium AZ31B Alloy. Magnesium alloys are an alternative to aluminium alloys. The elementary form of Magnesium does not occur in the nature because it reacts easily. For the extraction of Magnesium can be used two processes. One opportunity is the fused-salt electrolysis of melt magnesium chloride in downs-cells. The second opportunity is the thermal reduction of magnesia (pidgeon-process). Nowadays are produced about 400000 tons per year[115].

Components of the magnesium alloy are megnesium, alluminium, copper, calcium, nickel, iron, zinc, manganese and silicon[116]. The division of the components are presented in Table 9: Components of the magnesium alloy. 5.2 kg of the magnesium alloy were used for the thyssenkrupp SunRiser.

Magnesium alloys are used to harden aluminium alloys by an appendix of ≤ 5% magnesium. Besides magnesium is improving the weldability. Furthermore, magnesium alloys are used for packaging materials, running gears of airplanes and for parts of motorcycles and bicycles[117].

[115] Cf. CHEMIE.DE Information Service GmbH
[116] Cf. AZO Materials 2012
[117] Cf. CHEMIE.DE Information Service GmbH

Table 9: Components of the magnesium alloy

Components	Content in percent
Magnesium	97%
Aluminium	0.250-3.50%
Zinc	0.60-1.40%
Manganese	0.20%
Silicon	0.10%
Copper	0.050%
Iron	0.0050%
Nickel	0.0050%

The work with magnesium alloy AZ31B is easily. Magnesium alloys are light and have a high machinability. Handling with the magnesium alloy should be careful because it is flammable. When you are working with the magnesium alloy you should put on a magnesium fire arresting kit. The magnesium alloy AZ31B has a density of 1.77 g/cm. The thermal conductivity is 96 W/mK and the thermal expansion coefficient are 26 µm/m°C. At 260°C the magnesium alloy can be formed[118].
100% of Magnesium alloys are recyclable[119].
The following flowchart Figure 21: Magnesium alloy flowchart in GaBi of the magnesium alloy in GaBi shows the contribution of the magnesium alloy weight of 100 kg:

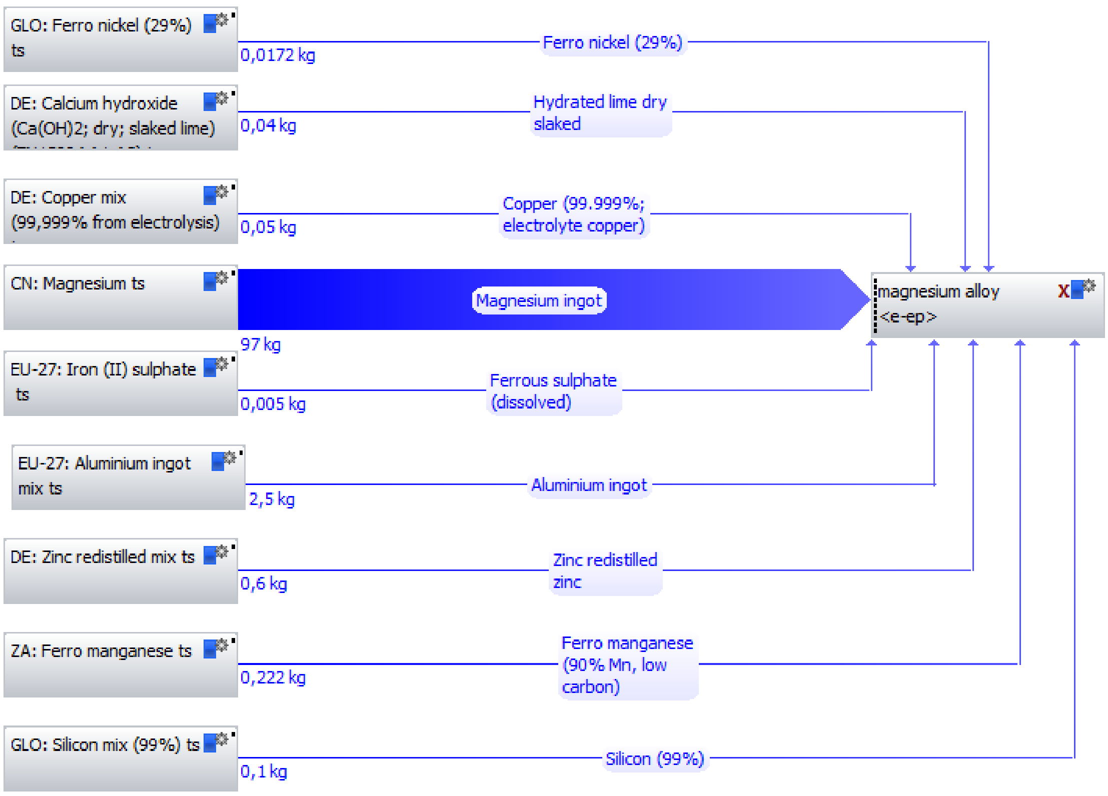


Figure 21: Magnesium alloy flowchart in GaBi

[118] Cf. AZO Materials 2012
[119] Cf. Magontec Group

3.2.12 Copper

Copper is a metal with the ability to conduct electricity and warmth very well. For that reason, it is an essential material for the thyssenkrupp SunRiser and the thyssenkrupp blue.cruiser. The metal is selected for the life cycle assessment because the production of copper is very deleterious to the environment.

Table 10: Ingredients of the used copper[120]

Ingredient	CU ETP1
Copper	99.9%
Bismuth	0.0005%
Oxygen	0.04%
Lead	0.005%

Native copper only exists in low quantities. Most copper can be found in sulphide and oxide ores, but just in a very low concentration. The leading copper ore deposits are in Chile, followed by Peru and the USA. 85 percent of the worldwide copper occurrences are sulphide ores[121, 122]. The first step of the copper production (see Figure 22: Copper production) is the exploitation of the copper ore by mining, followed by different methods to achieve a higher copper concentration. The first process is the flotation. This method can only be used for sulphide ores. The aim is the separation of hydrophilic and hydrophobic materials. According to this fact, the method does not work for oxide ore. Instead, for these ores a leaching with e.g. diluted sulfuric acid is used to enrich the copper. The result of these production steps is a copper concentration at about 20 to 30 percent[123].

The next step of the hydrometallurgy processing for copper, based on oxide ore, is the extraction with solvent to gain raw copper. The raw copper is an intermediate product in the copper production. The result is a copper cathode, which can be used to produce copper wires, tubes or sheets after additional treatments. The copper cathode has a concentration at about 99.95%[124].

The pyrometallurgy processing for sulphide ore works in a different way as the hydrometallurgy processing. After the flotation, the extracted copper concentrate is smelted to receive copper matte. The copper content of the matte is between 30 and 80 percent. After that, the copper matte is converted into blister copper with a copper concentration between 96 and 99 percent and the by-product sulfuric acid. The fire refinery converts the blister copper into anode copper. The final product is the copper cathode after the electrolytic refinery, which separates metals like gold or silver from the anode copper.

120 Deutsches Kupferinstitut Berufsverband e.V. 2017b, 2
121 Cf. Deutsches Kupferinstitut Berufsverband e.V. 2017d
122 Cf. Deutsches Kupferinstitut Berufsverband e.V. 2017c
123 Cf. Deutsches Kupferinstitut Berufsverband e.V. 2017c
124 Cf. Deutsches Kupferinstitut Berufsverband e.V. 2017c

During the first three steps of the pyrometallurgy processing, slag is produced. The slag is led back to the part of the process where the copper concentrate is smelted to extract remaining copper[125].

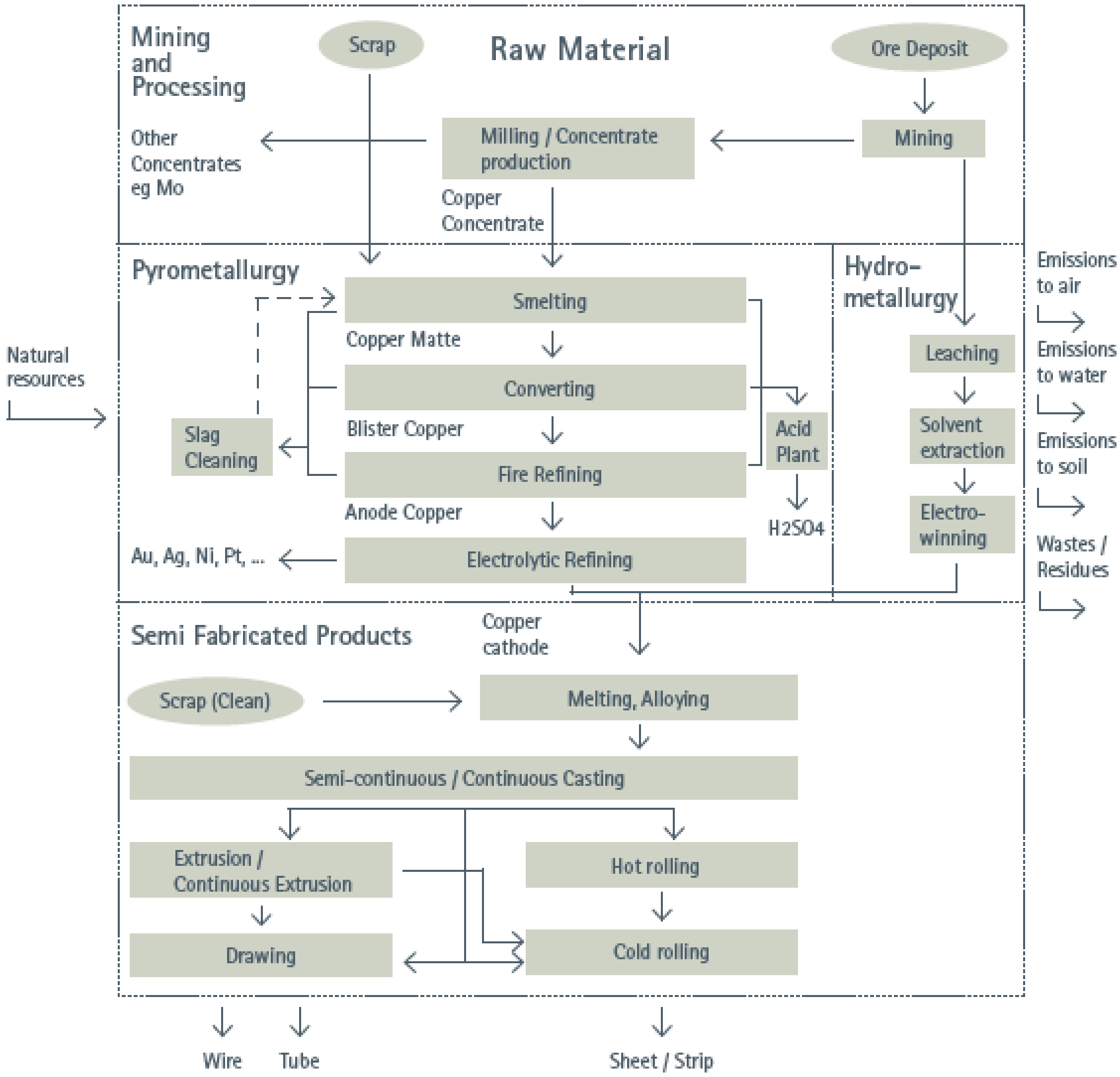


Figure 22: Copper production[126]

Copper is used for the electric cables and the litz of the motor in the thyssenkrupp SunRiser. The copper wires in the cables weight at about 9.5 kg. A part of the motor is the copper litz, which weights at about 20 kg. In total, 31.9 kg in the SunRiser and 27.1 kg in the blue.cruiser have been installed (see Table 1: ABC analysis SunRiser weight and Table 2: ABC analysis blue.cruiser weight).

Copper is 100 percent renewable without any loss of quality. This applies for copper scrap, which is generated during production and material in form of end-of-life products. In a first step of recycling, the copper is sorted. After that, the material is melted down in an induction furnace[127].

[125] Cf. Deutsches Kupferinstitut Berufsverband e.V. 2017c
[126] European Copper Institute 2012, 6
[127] Cf. Deutsches Kupferinstitut Berufsverband e.V. 2017a

The entire modelling of copper litz is shown in Figure 23: Copper litz flowchart in GaBi.

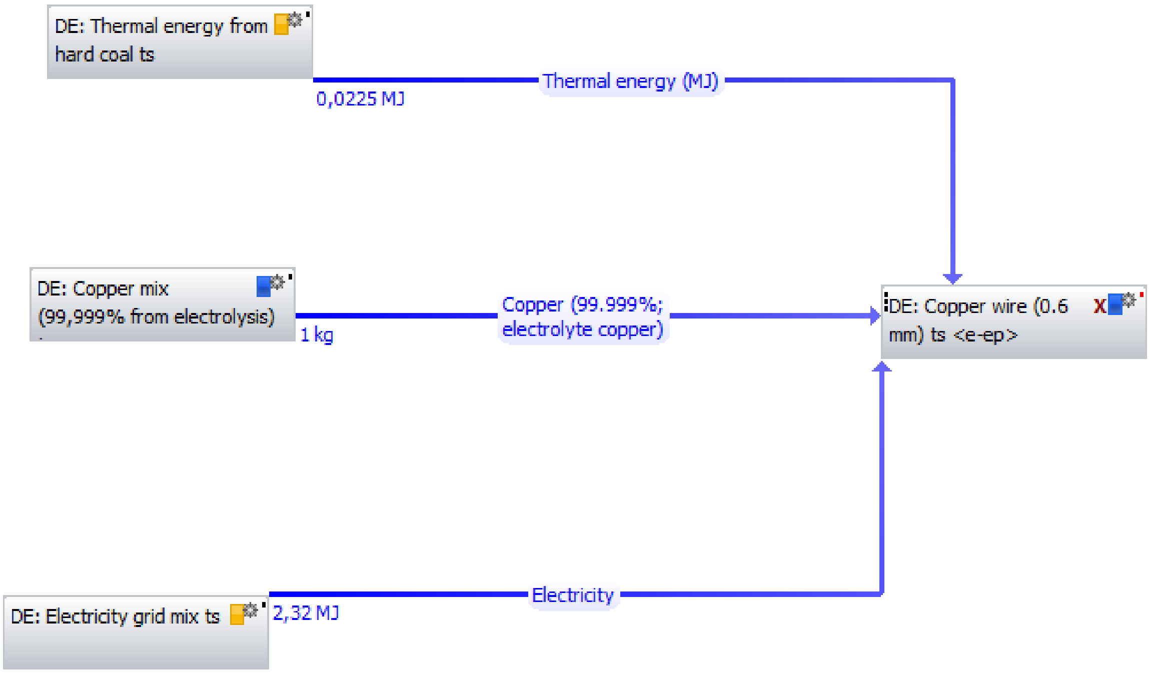


Figure 23: Copper litz flowchart in GaBi

3.2.13 Polyvinyl chloride (PVC)

Polyvinyl chloride is a thermoplastic polymer, which has, because of its different qualities, a wide range of applications like cables, pipes, bottles or plates. The polymer can be in a soft (PVC-P) and rigid state (PVC-U), furthermore is the production very cheap[128, 129].

To produce PVC, two raw materials are needed (see Figure 24: PVC production). On the one hand, crude oil is necessary to receive ethylene with the help of a refinery and a steam cracker. The other part is chlorine, which is gained by treating rock salt with the chlorine-alkali electrolysis. By compounding the ethylene and chlorine, vinyl chloride is extracted. The vinyl chloride is the primary product of PVC. The next step is the polymerization process, which can be subdivided into three different techniques. The first way is the emulsion polymerization (E-PVC), the second is the suspension polymerization (S-PVC) and the last one is the mass polymerization (M-PVC). To receive PVC material with the desired properties, additives like stabilizer and softening agents are added[130].

[128] Cf.AGPU e.V. 2016, 3, 6 f.
[129] Cf.European Commission 2004, 74
[130] Cf.AGPU e.V. 2016, 4 ff.

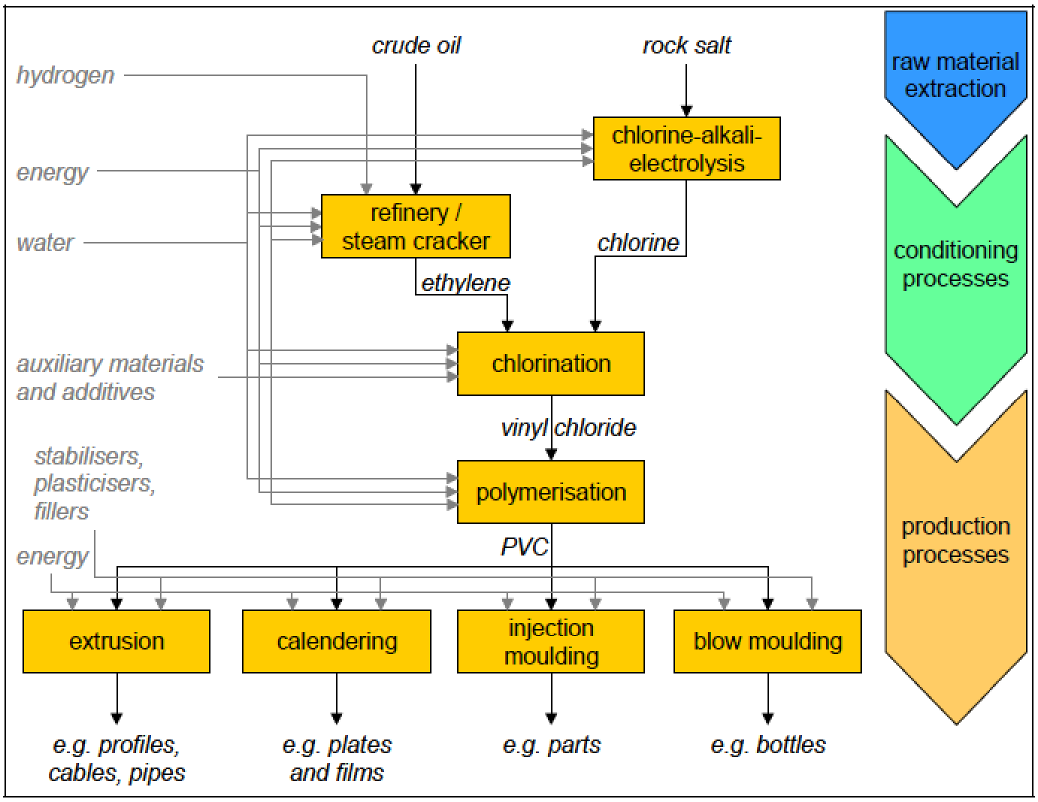


Figure 24: PVC production[131]

PVC is the insulation material of most of the electric cables which are used in the thyssenkrupp SunRiser. To be more precisely the cables for the battery and the whole wiring of the lights and the solar cells have PVC insulation. Altogether at about 2.7 kg PVC casing is installed in the thyssenkrupp SunRiser and 3.56 kg in the thyssenkrupp blue.cruiser (see Table 1: ABC analysis SunRiser weight and Table 2: ABC analysis blue.cruiser weight).

There are three different ways to handle with the PVC waste. The most common way is the recycling of the waste by reclaiming PVC. This material has a lower quality because the polymer chains are shorter as the primary PVC material. This special kind of recycling is called downcycling due to the lower quality standards of the plastic. Owing to new techniques, it is also possible to receive secondary PVC of plastic, which is polluted with other materials[132].

If the material cannot be transformed into PVC again, it is separated into its petrochemical raw materials. In case of the PVC, hydrogen chloride is obtained. This can be used for the primary PVC production again. Another raw material is hydrocarbon, which is useful for the electricity generation[133].

[131] European Commission 2004, 74
[132] Cf.AGPU e.V. 2016, 9
[133] Cf.AGPU e.V. 2016, 9

The last method to deal with the waste is the energetic recycling. In this case the waste material is burned. Due to released hydrogen chloride during the process, lime and filter are needed to neutralize. The remaining calcium chloride is dumped on a disposal[134].

3.2.14 Usage scenario

The usage scenario for both SolarCars is based on the assumption that the cars are used fully loaded to drive 50 kilometres in the span of an hour each day. Furthermore, each SolarCar has an expected useful life of ten years and therefore drives 182,500 kilometres in total throughout it. Based on the assumption that the tyres used for the SolarCars last for 20,000 kilometres, nine sets of tyres are needed in total for each car (see 3.2.1 Tyres).

To ensure the highest possible insolation it is assumed that the cars are only parked in spots that can be reached by sunbeams and not in underground car parks or garages. The values for the whole insolation throughout the life span of the SolarCars are based on data from the year 2016[135]. The average insolation has been computed for each month of 2016 and has been set off against the area of the solar cells of each car and its efficiency factor, as can be seen in Table 11: Insolation of SunRiser and blue.cruiser; reference location: Bochum[135]. While the GaAs solar cell of the thyssenkrupp SunRiser has an area of three sqm and an efficiency factor of 0.292, the silicon solar cell of the thyssenkrupp blue.cruiser has an area of 4.865 sqm and an efficiency factor of 0.234.

Table 11: Insolation of SunRiser and blue.cruiser; reference location: Bochum[135]

Month	insolation [kWh/sqm]	SunRiser	blue.cruiser
		Insolation [kWh]	insolation [kWh]
January	23	20.15	26.19
February	38	33.29	43.26
March	68	59.57	77.42
April	113	98.99	128.65
May	108	94.61	122.96
June	143	125.27	162.81
July	158	138.41	179.88
August	128	112.13	145.73
September	113	98.99	128.65
October	48	42.05	54.65
November	23	20.15	26.19
December	18	15.77	20.49
TOTAL [kWh/a]	**981**	**859.38**	**1116.88**

[134] Cf.AGPU e.V. 2016, 9 f.
[135] EEM Energy & Environment Media GmbH i.Gr.

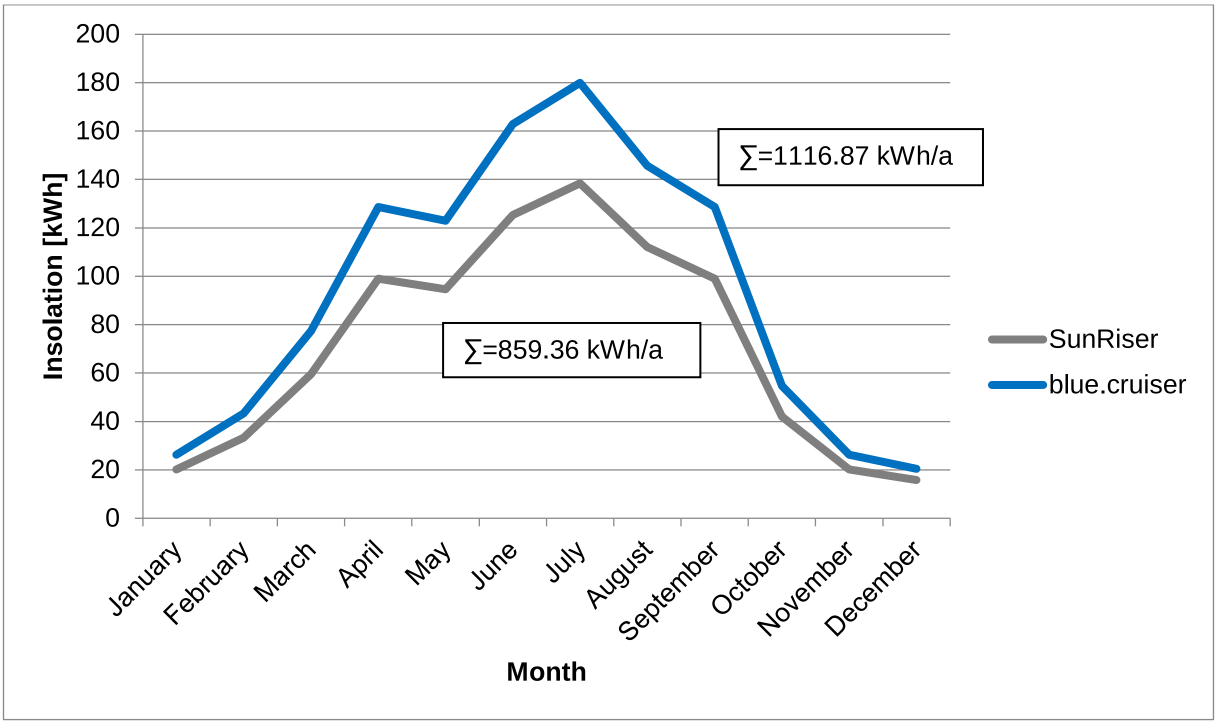


Figure 25: Electricity generation of SunRiser and blue.cruiser per month; reference location: Bochum

Therefore, the insolation for the SunRiser amounts to 859.36 kWh per year and 8,593.56 kWh for its entire life span, whereas the insolation for the blue.cruiser amounts to 1,116.87 kWh per year and 11,168.72 kWh in total.

Note: An average fridge has an energy consumption of less than 130kwh per year:

Table 12: Energy consumption of fridges per year

Manufacturer	Model designation	Size [l]	Energy consumption [kWh/a]
Siemens	KS36VVL40	346	75
Liebherr	TPesf 1710	147	94
Bosch	KSV29NW30	290	107
Beko	TSE 1422	130	119
Amica	EVKS 16325	204	129

To compute the mileage of each car with the given usage scenario, the New European Driving Cycle (NEDC) has been used. The outcome of this calculation is that the SunRiser has a mileage of 0.033 kWh per km while the blue.cruiser has one of 0.039 kWh per km. Therefore, the total energy demand over the whole life cycle accounts to 5,967.8 kWh and 7,081 kWh for each car respectively. Consequently the surplus electricity that each car can feed back into the main grid over the course of its entire life span, amount to 2,625.8 kWh and 4,087.7 kWh respectively for the SunRiser and blue.cruiser, shown in Table 13: Total surplus electricity:

Table 13: Total surplus electricity

	total insolation [kWh]	total energy demand [kWh]	surplus electricity [kWh]
SunRiser	8,593.56	5,967.8	2,625.8
blue.cruiser	11,168.72	7,081	4,087.7

3.2.15 End of life

The end of life is separated in three phases. As shown in the figure 23, three parts could be pre-treated. This is rubber, GFRP and the battery. The most components are dismantling parts: a part of CFRP, aluminium alloy, a part of NFRP, acrylic glass, all steel parts, neodymium, copper, PVC and the solar panel. The other components (a part of CFRP, ROHACELL® and a part of NFRP) will be shredded.

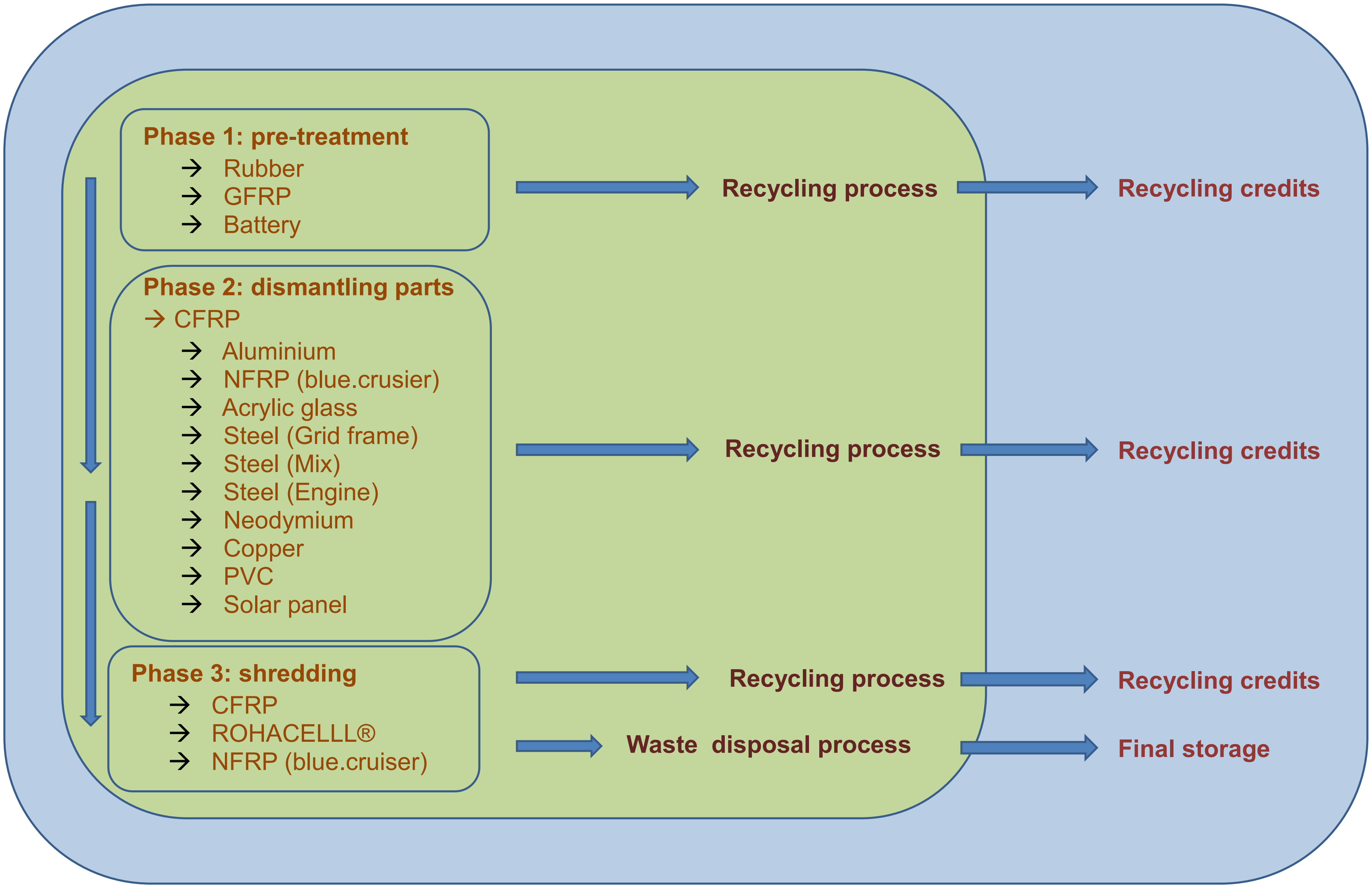


Figure 26: End of life

4 Impact assessment

In this chapter, the life cycle impact assessment results are presented for the production and disposal of one solar-powered vehicle in Germany. The statements refer to the life cycle of the thyssenkrupp SunRiser and the thyssenkrupp blue.cruiser.

4.1 Global warming potential

The Global Warming Potential (GWP) describes the potential contribution of the processing steps to the greenhouse effect, i.e. climate change.

The global warming phenomenon is mainly associated with carbon dioxide emissions. *“Carbon dioxide emissions are mainly associated with the conversion of fossil energy carriers (e.g. lignite, crude oil, natural gas) into thermal and/or mechanical energy by means of burning and are expressed in kilograms of CO_2.”*[136] The carbon dioxide emissions of the LCI are illustrated in Figure 27: Comparison of GWP in the different phases [kg CO_2-eq.].

In total, 10300 kg CO_2-equivalents are emitted by the different life steps of thyssenkrupp SunRiser, and 9370 kg CO_2-equivalents are emitted by the thyssenkrupp blue.cruiser. This means an improvement of 9%.

The greenhouse gas emissions are closely linked to the production of the battery, the CFRP body in white, and the solar cells, which account for 80% of the total emissions for the production sector. The most significant savings were achieved by changing the solar cell type from GaAs to Si, which emit more than 60% less greenhouse gases.

In contrast, the power generation in the use phase reduces the GWP by 1570 kg CO_2 equivalents for the thyssenkrupp SunRiser, and 2470 kg CO_2 equivalents for the thyssenkrupp blue.cruiser.

Credits can also be achieved through targeted recycling and disposal, while thyssenkrupp SunRiser achieves a 24% higher value since it weighs less.

[136] The Aluminium Association, 2013

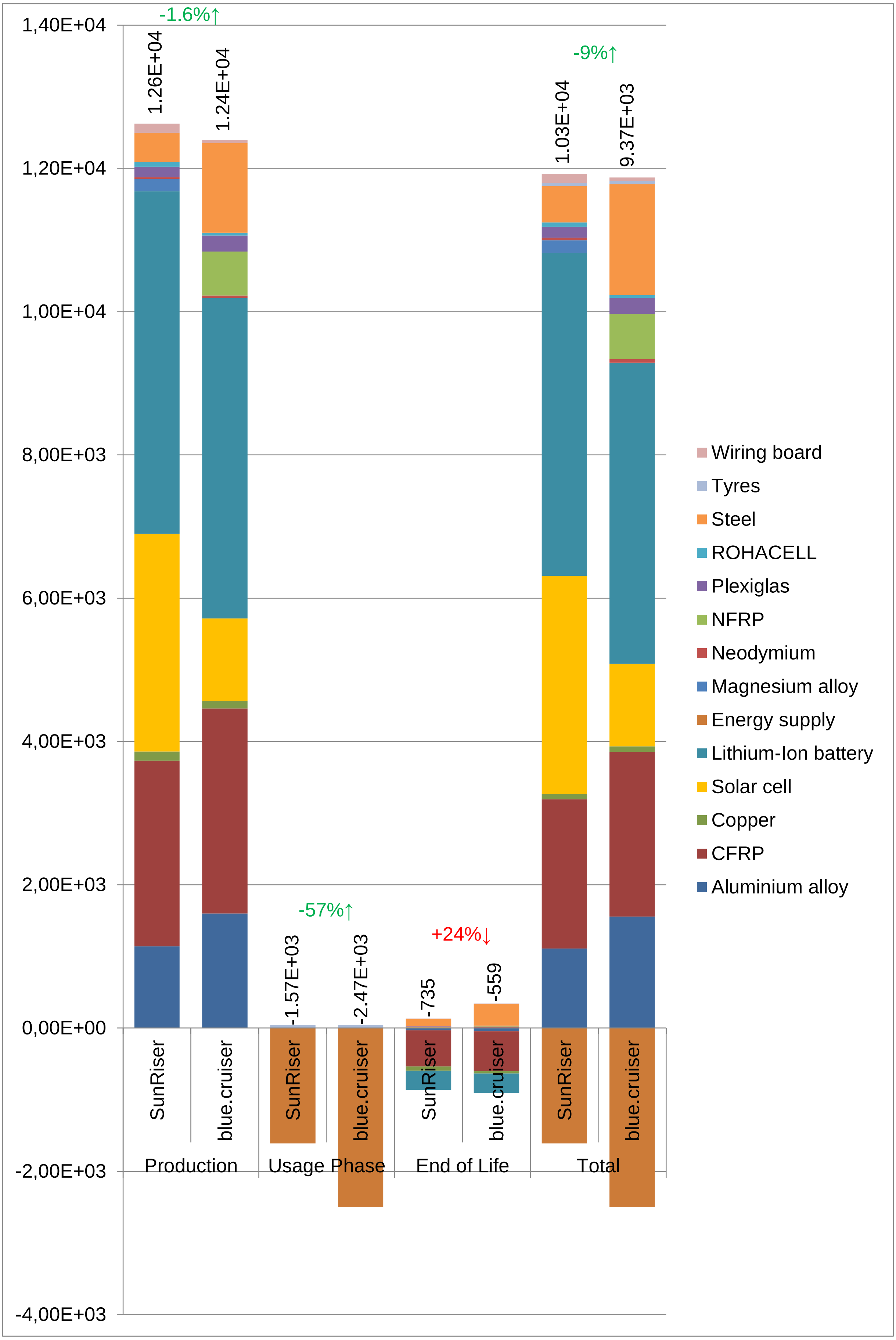


Figure 27: Comparison of GWP in the different phases [kg CO_2-eq.]

4.2 Acidification potential

Acidification is understood as the increasing concentrations of H + ions in air, water, and soil. Sulfur and nitrogen compounds from anthropogenic emissions react (in the air) to sulfuric or nitric acid, which fall to earth as acid rain and damage soil, aquatic organisms, and buildings. So, the acidification potential causes acidifying effects to the environment. It is expressed in kilogram SO_2 equivalents. The amounts of the SolarCar structure production are shown in Figure 28: Comparison of AP in the different phases [kg SO_2-eq.].

Breaking the emissions down by manufacturing steps shows that the battery construction is responsible for over 80% of the total acidification potential results for the thyssenkrupp blue.cruiser. At the thyssenkrupp SunRiser the battery construction has an influence of 50%, while additionally the GaAs solar cells have an influence of 27%. In comparison blue.cruiser to SunRiser, 42% less influences were caused over the whole life cycle.

It is also to note that proper disposal reduces over 11% of the acidification potential impacts.

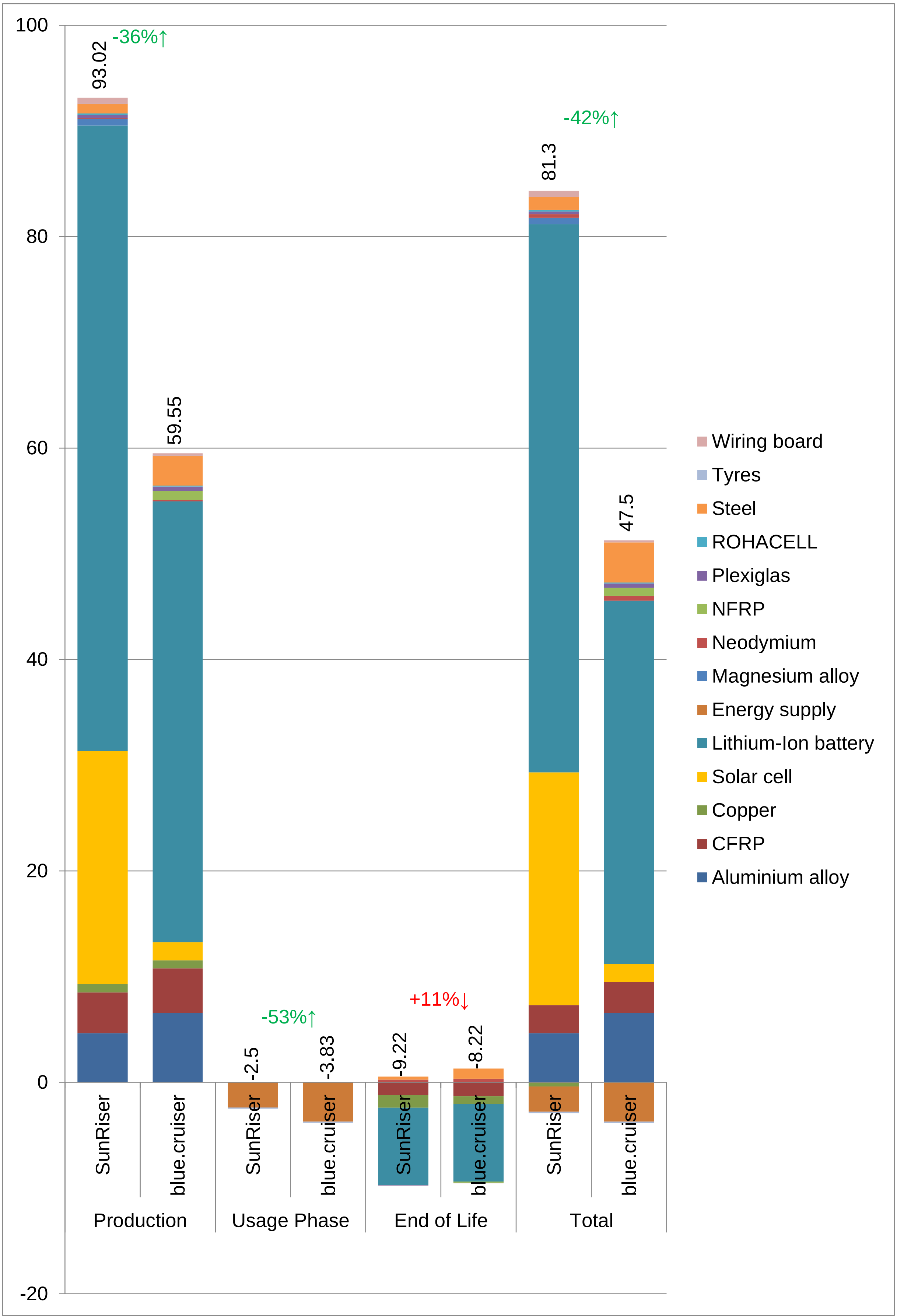


Figure 28: Comparison of AP in the different phases [kg SO_2-eq.]

4.3 Eutrophication potential

As mentioned above, eutrophication means over-fertilization resulting from too much nutrient supply and consequently increased oxygen consumption. Human causes eutrophication. A distinction is made between aquatic and terrestrial eutrophication. In this impact category, ammonia, nitrate (N-compounds) and phosphate (P-compounds) are the leading causes. All these substances are converted into the P-equivalents.

The total eutrophication potential related to the production of solar-powered vehicle in Germany is 12.2 kg phosphate equivalents for the thyssenkrupp SunRiser and 12.1 kg phosphate equivalents for the thyssenkrupp blue.cruiser, which means nearly the same (1% difference).

A breakdown of the results by individual production stages is shown in Figure 29: Comparison of EP in the different phases [kg phospate-eq.]. The figure shows that 75% of the eutrophication impacts come from lithium ion battery, for both solar cars. The life cycle of neodymium magnets is the next largest contributor with 8% share of eutrophication potential. The usage of the vehicles has less than 5% share of the eutrophication impact, also it has a positive influence through the energy generation.

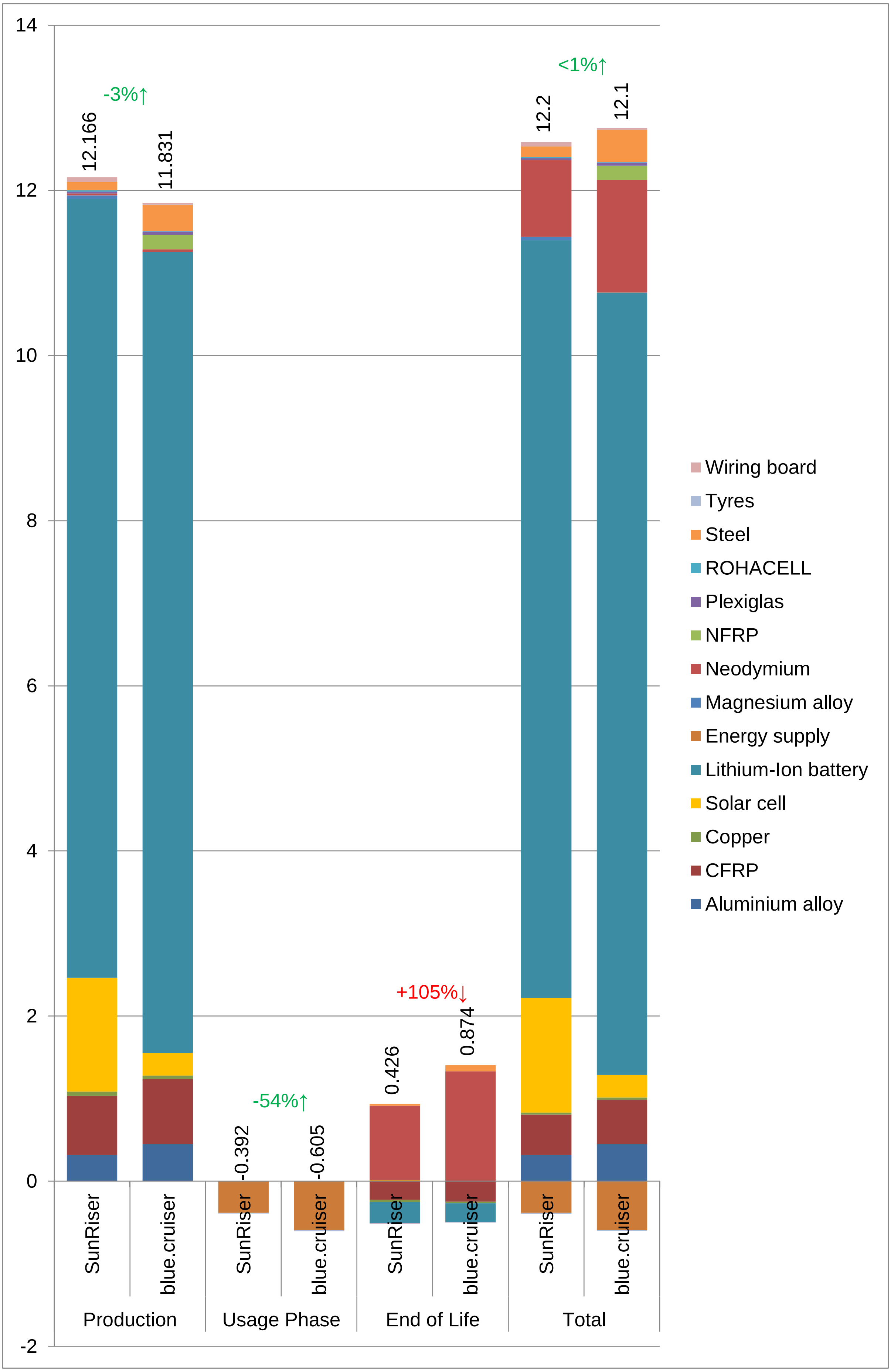


Figure 29: Comparison of EP in the different phases [kg phospate-eq.]

4.4 Ozone depletion potential

The Ozone Depletion Potential (ODP) describes the potential of substances that degrade the protective layer of ozone and thus contributes to ozone hole formation. The causes of ozone depletion are primarily free-radical chlorine atoms from chlorinated organic compounds, which are collectively referred to as chlorofluorocarbons (CFCs).

The major emissions are trichlorofluoromethane (R11) and dichlorodifluoromethane (R12). The Ozone Layer Depletion Potential related to 1 SolarCar structure in Germany amounts to 7.35E-07 kg R11 equivalents for the thyssenkrupp SunRiser and 6.02E-07 R11 equivalents for the thyssenkrupp blue.cruiser (Figure 30: Comparison of ODP in the different phases [kg R11-eq.]). Through a more intelligent material selection, the blue.cruiser avoided 18% emissions compared to its predecessor.

The chlorofluorocarbon compound load is very low in all manufacturing processes, with 2.4E-06 kg R11 equivalents for the SunRiser and 3.52E-06 kg R11 equivalents for the blue.cruiser, having the highest value in neodymium production. This is due to the fact that the 4-wheel drive in the blue.cruiser has more magnets installed.

It is also noticeable that the flax components have a significant influence on the result in both production and disposal (blue.cruiser). The usage remains nearly the same.

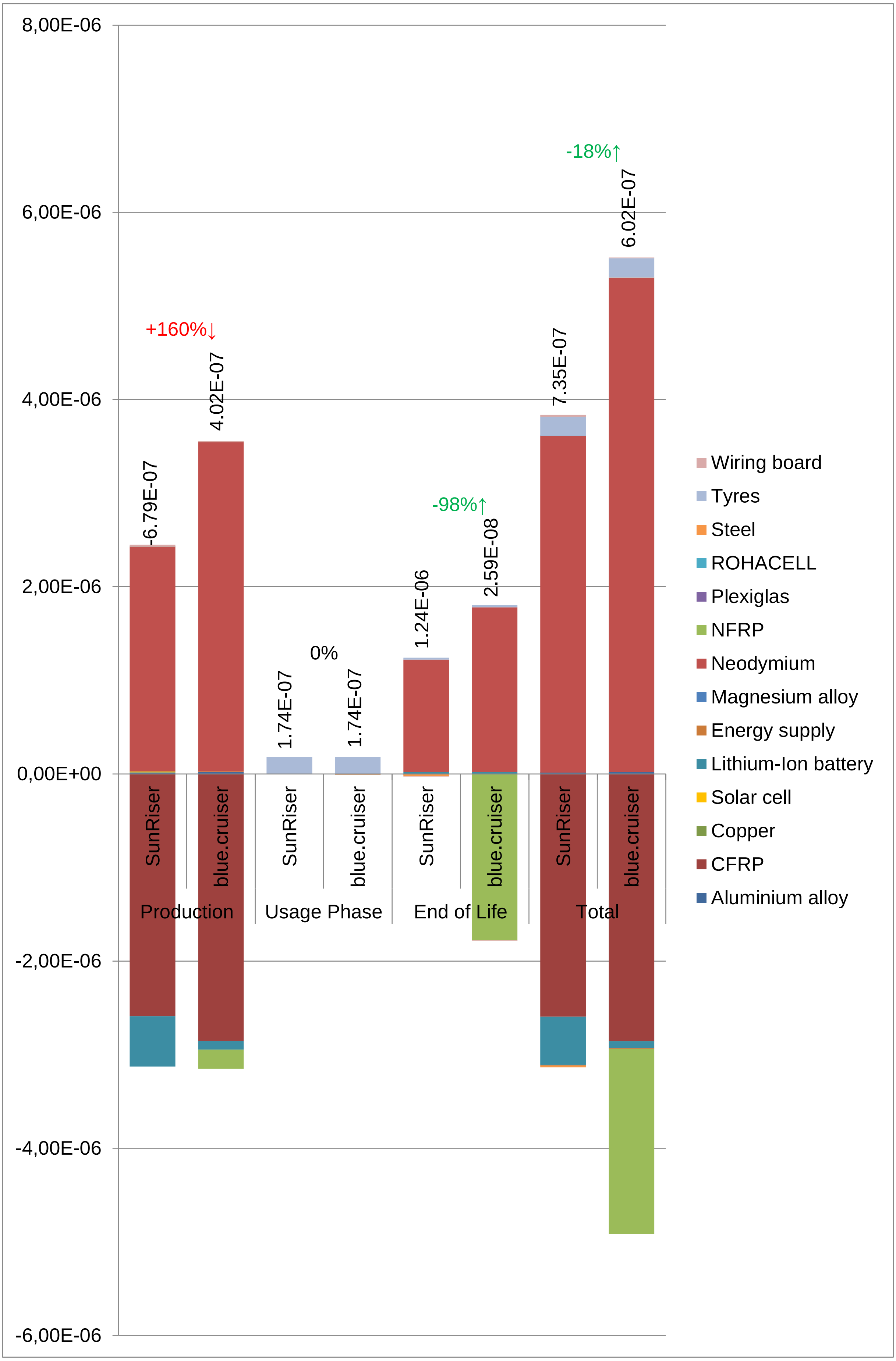


Figure 30: Comparison of ODP in the different phases [kg R11-eq.]

4.5 Abiotic depletion potential

ADP refers to the consumption of non-biological resources such as fossil fuels. The value of the abiotic resource consumption of a substance is a measure of the scarcity of a substance. That means it depends on the amount of resources and the extraction rate. The impact category is measured in MJ.

In a comparison between SunRiser and blue.cruiser, the effects on the abiotic depletion potential (ADP) are in favor of the SunRiser. In total, the thyssenkrupp SunRiser has a demand of 1.43E+05 MJ and the thyssenkrupp blue.cruiser of 1.95E+05 MJ, which means a 36% higher consumption.

In the utilization phase, both cars behave again positively. The generation of electric energy does not require the conversion of fossil fuels, the surplus can be credited. Since the blue.cruiser can generate more energy, its values turn out 56% better for the usage.

In the production 90% of the demand is caused by the production of steel, aluminum, battery and CFRP. Caused by higher material requirements, the blue.cruiser achieves a 20% higher demand.

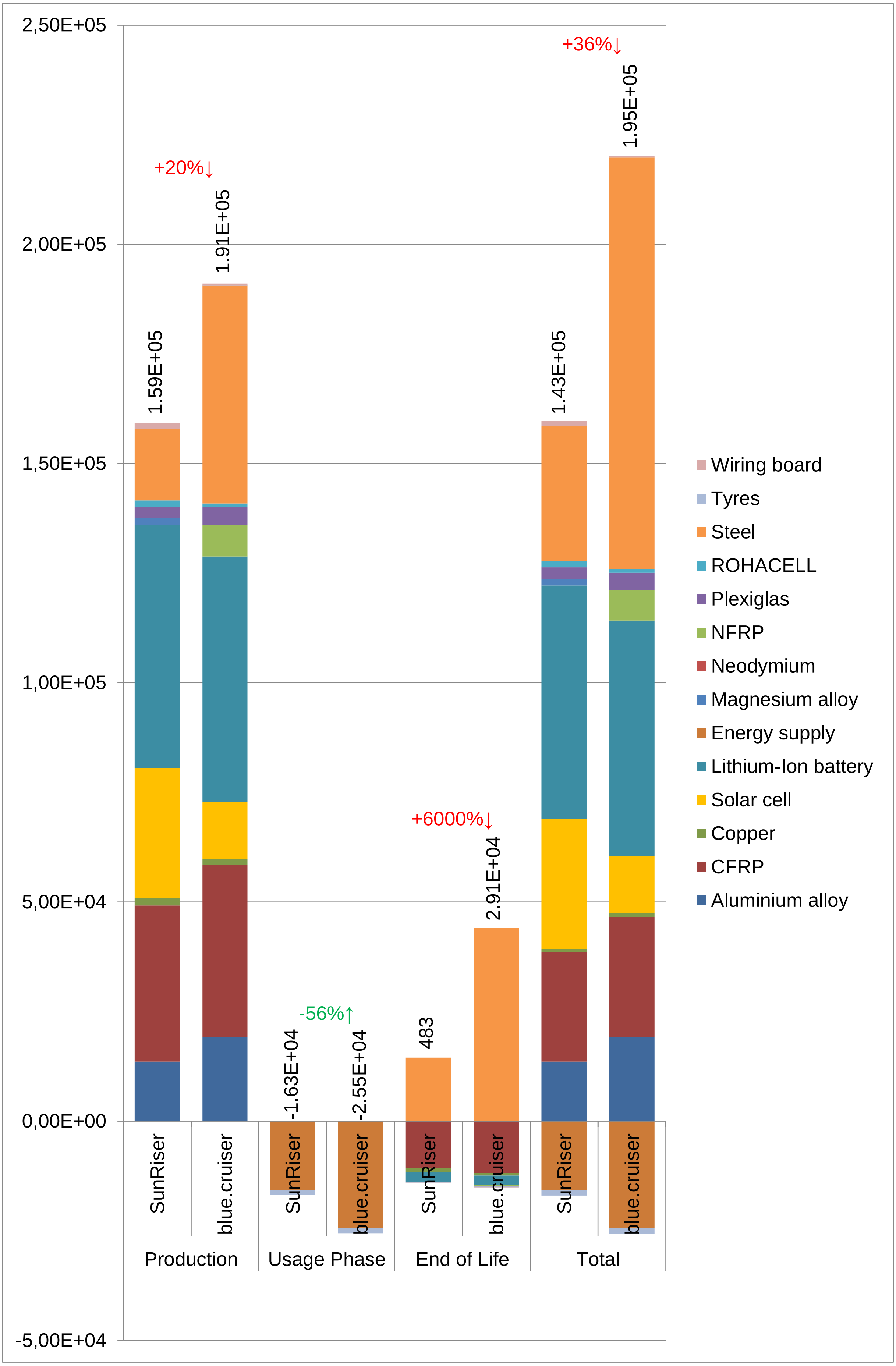


Figure 31: Comparison of ADP in the different phases [MJ]

4.6 Freshwater aquatic ecotoxicity potential

FAETP describes the potential for biological, chemical or physical stressors to affect the ecosystems. These stressors might occur in the natural environment to disrupt the natural bio-chemistry, behavior and interactions of the living organisms that comprise the ecosystem. The emission of some substances, such as heavy metals, can have impacts on the ecosystem. Ecotoxicity potentials are calculated with the method for describing fate, exposure and the effects of toxic substances on the environment. The freshwater aquatic ecotoxicity potential is measured in kg 1.4-DCB equivalents.

In total, 127 kg 1.4-DCB equivalents are emitted by the different life steps of thyssenkrupp SunRiser, and 160 kg 1.4-DCB equivalents are emitted by the thyssenkrupp blue.cruiser. This means an worsening of 26%.

The FAETP is closely linked to the production of the battery, which account for 70% of the total impact for the production sector. The most significant savings were achieved by changing the solar cell type from GaAs to Si, which causes more than 40% less impacts.

In contrast, the power generation in the use phase reduces the FAETP by 2.2 kg 1.4-DCB equivalents for the thyssenkrupp SunRiser, and 3.25 kg 1.4-DCB equivalents for the thyssenkrupp blue.cruiser.

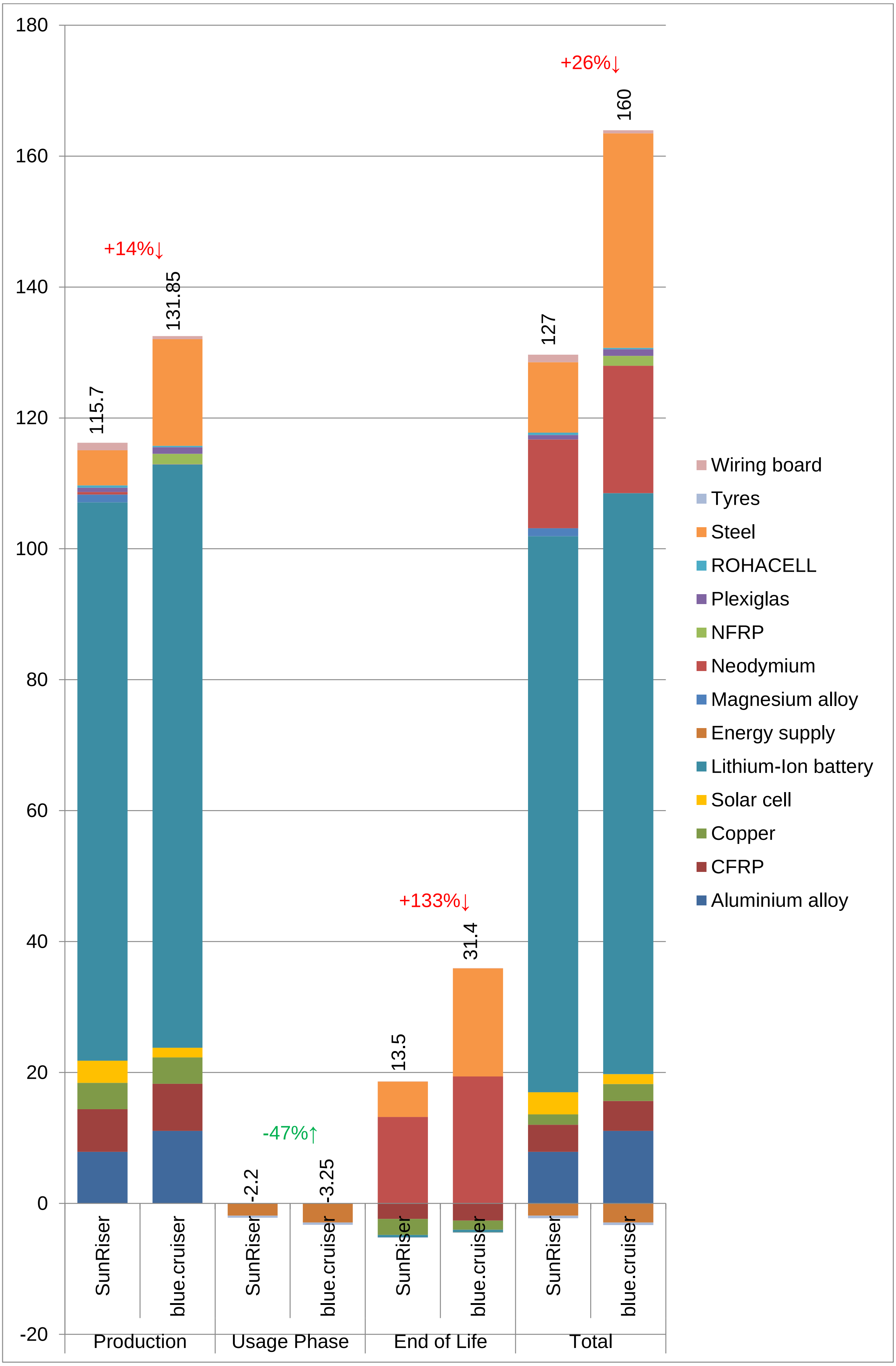


Figure 32: Comparison of FAETP in the different phases [kg DCB-eq.]

4.7 Human toxicity potential

The human toxicity potential deals with numerous toxic substances, such as heavy metals and organic substances which directly harm human beings. It includes toxic effects of chemicals on humans. There are potentially dangerous chemicals to humans through inhalation, ingestion and even contact. Cancer potency, for example, is an issue here. The unit in which is measured is kg 1,4-DCB equivalents.

The effects on human toxicity potential can be attributed to the lithium battery and aluminum in both cars. The lithium battery in the blue.cruiser has 4810 kg of DCB-eq. and 4440 kg DCB-eq. in the SunRiser, aluminum completes the effects of the HTP with 5420 kg DCB-eq. and 3840 kg DCB-eq. almost completely. In total result 10500 kg DCB-eq. (blue.cruiser) and 8540 kg DCB-eq. (SunRiser)) of the life cycle phases of the HTP are caused, which means a deterioration of 23% for the blue.cruiser.

The performance of the SunRiser during the production phase (10600 kg DCB-eq. (blue.cruiser) and 8700 kg DCB-eq. (SunRiser)) allows the SunRiser to show slightly better values overall.

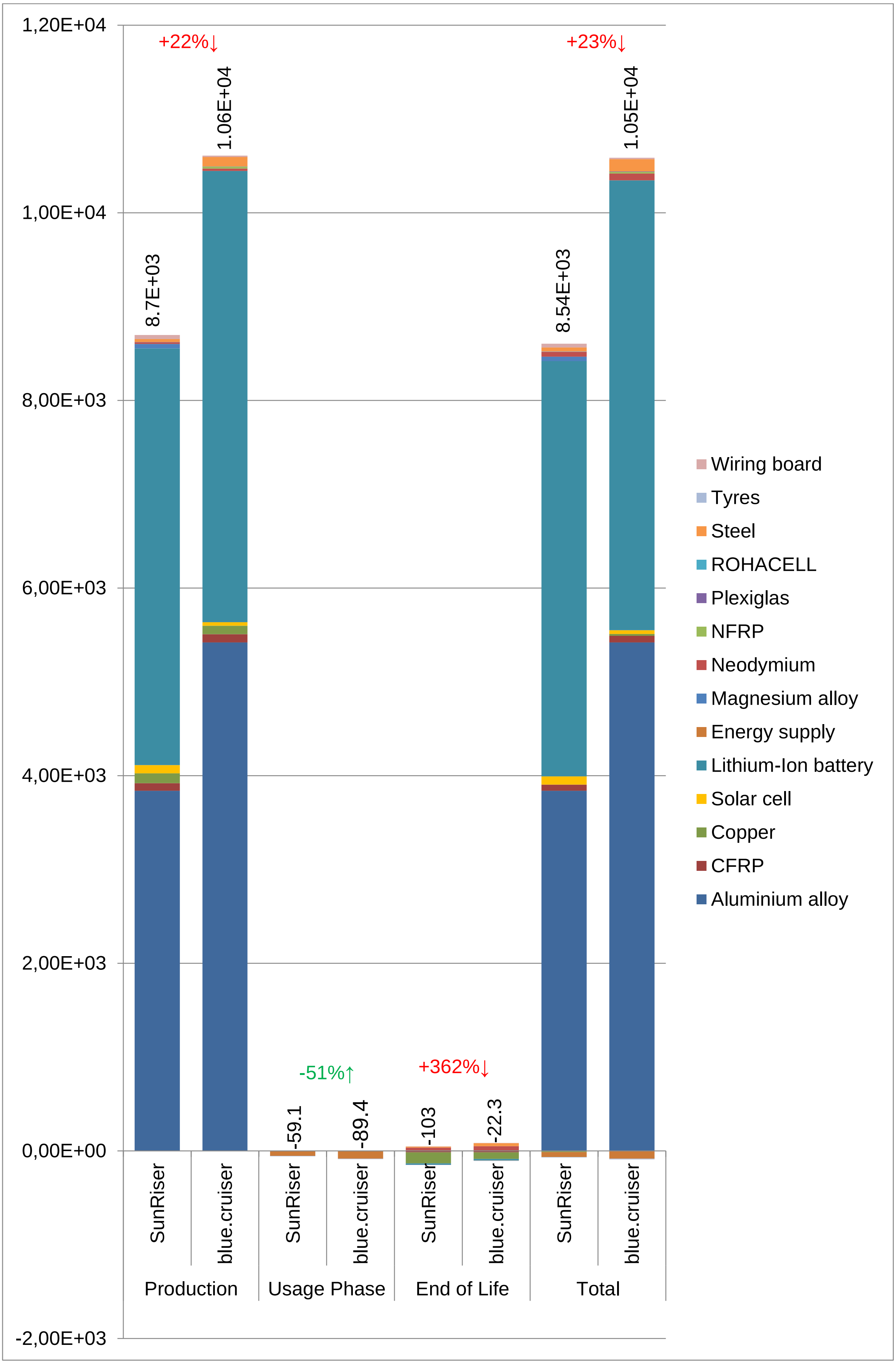


Figure 33: Comparison of HTP in the different phases [kg DCB-eq.]

4.8 Photo oxidation creation potential

The photochemical ozone creation potential, also called Smog Formation Potential, measures the emissions of precursors that contribute to low level smog (also called summer smog). The main reasons for this Summer Smog, which can generally be translated with air pollution, are various chemical and physical processes in the environment, as the reaction of NOx and volatile organic compounds (VOC) under the influence of ultra violet light. The different gases that contribute to this impact category are summarized under kg ethene equivalents.

The POCP results are illustrated in Figure 34: Comparison of POCP in the different phases [kg ethene-eq.].

Like the other life cycle impact categories, the battery is the largest contributor to summer smog creation impacts, accounting over 60% of the total POCP. This is followed by aluminum and steel production, which is responsible for over 10% of the photochemical ozone creation potential.

The effects for photo oxidation creation potential are mainly determined by lithium ion battery. Here the effects of the POCP are 3.16 kg ethene-eq. (blue.cruiser) and 3.83 kg ethene-eq. (SunRiser). In all three phases, the blue.cruiser cuts off slightly better. In both cars, the end-of-life and usage values can be calculated negatively (utilization phase: -0.268 kg ethene-eq. (blue.cruiser) and -0.176 kg ethene-eq. (SunRiser), End of Life: -0.306 kg ethene-eq. (blue.cruiser) and -0.427 kg ethene-eq. (SunRiser)). The total result shows an improvement of the thyssenkrupp blue.cruiser by 73%.

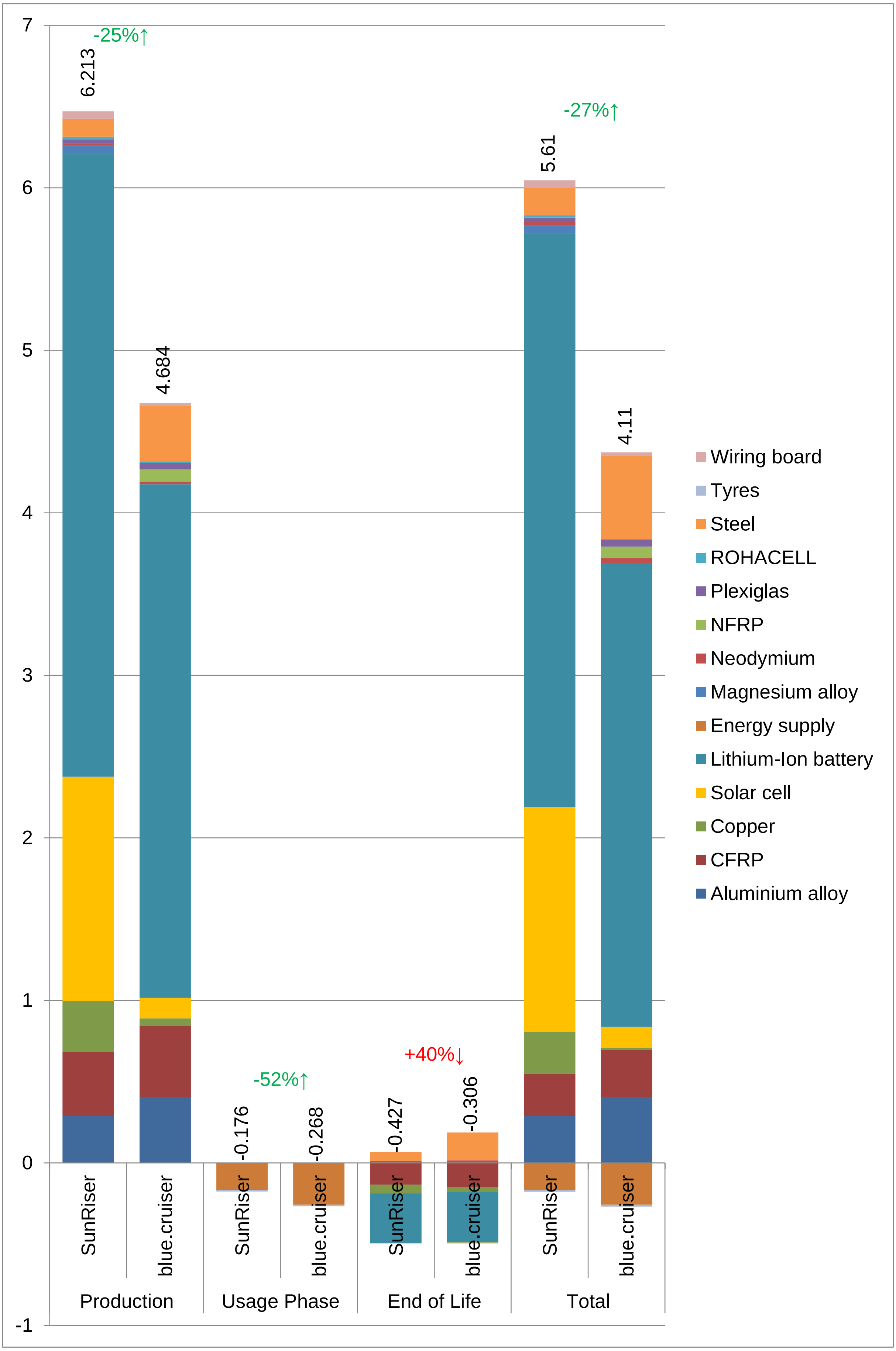


Figure 34: Comparison of POCP in the different phases [kg ethene-eq.]

Table 14: Impact assessment data (1)

	GWP		AP		EP		ODP	
	kg CO_2-eq		kg SO_2-eq		kg P-eq		kg R11-eq	
	SunRiser	**blue.cruiser**	**SunRiser**	**blue.cruiser**	**SunRiser**	**blue.cruiser**	**SunRiser**	**blue.cruiser**
Aluminium	1.14E+03	1.60E+03	4.65	6.55	0.318	0.449	1.30E-08	1.83E-08
CFRP	2.59E+03	2.86E+03	3.85	4.24	0.715	0.788	-2.59E-06	-2.85E-06
Copper cable	45.9	58.8	0.378	0.483	0.016	0.021	6.98E-10	8.93E-10
Copper litz	82.5	48.9	0.44	0.261	0.036	0.022	2.68E-09	1.59E-09
Lithium battery	4.78E+03	4.47E+03	59.2	41.7	9.43	9.7	-5.37E-07	-9.59E-08
Magnesium	173	-	0.63	-	0.044	-	2.68E-10	-
Neodymium	25.2	37	0.084	0.123	0.022	0.032	2.40E-06	3.52E-06
NFRP	-	615	-	0.871	-	0.176	-	-2.05E-07
Plexiglas	147	223	0.266	0.405	0.025	0.038	1.26E-10	1.92E-10
ROHACELL	63.2	37.7	0.144	0.086	0.016	0.009	8.00E-11	4.76E-11
Solar cells	3.04E+03	1.15E+03	22	1.72	1.38	0.274	9.49E-09	4.31E-09
Steel	410	1.25E+03	0.929	2.84	0.103	0.316	1.57E-09	4.81E-09
Tyres	0.326	0.332	0.001	0.001	1.94E-04	0.002	9.63E-10	9.80E-10
Wiring board	127	48	0.571	0.215	0.055	0.021	1.92E-08	7.24E-09
Usage	-1.57E+03	-2.47E+03	-2.5	-3.83	-0.392	-0.605	1.74E-07	1.74E-07
End of life	-735	-559	-9.22	-8.22	0.426	0.874	1.24E-06	2.59E-08
Total	1.03E+04	9.37E+03	81.3	47.5	12.2	12.1	7.35E-07	6.02E-07

Table 15: Impact assessment data (2)

	ADP fossil		FAETP		HTP		POCP	
	MJ		kg DCB-eq		kg DCB-eq		kg Ethene-eq	
	SunRiser	**blue.cruiser**	**SunRiser**	**blue.cruiser**	**SunRiser**	**blue.cruiser**	**SunRiser**	**blue.cruiser**
Aluminium	1.36E+04	1.92E+04	7.88	11.1	3.84E+03	5.42E+03	0.288	0.406
CFRP	3.56E+04	3.92E+04	6.51	7.17	79	87.1	0.395	0.436
Copper cable	649	830	0.835	1.07	39.3	50.3	0.023	0.03
Copper litz	1.02E+03	603	3.19	1.89	67.1	39.8	0.029	0.017
Lithium battery	5.54E+04	5.6E+04	85.3	89.1	4.44E+03	4.81E+03	3.83	3.16
Magnesium	1.52E+03	-	1.21	-	49.8	-	0.055	-
Neodymium	-	-	0.037	0.054	16.4	24	0.01	0.015
NFRP	-	7.13E+03	-	1.56	-	20.8	-	0.076
Plexiglas	2.67E+03	4.06E+3	0.674	1.03	2.06	3.13	0.027	0.041
ROHACELL	1.46E+03	868	0.357	0.212	1.43	0.854	0.015	0.009
Solar cells	2.97E+04	1.3E+04	3.38	1.49	87.3	38.8	1.38	0.127
Steel	1.63E+04	4.97E+04	5.34	16.3	32.1	98	0.112	0.341
Tyres	9.18	9.35	0.005	0.005	0.035	0.036	1.06E-04	1.08E-04
Wiring board	1.26E+03	473	1.16	0.438	41.5	15.6	0.046	0.018
Usage	-1.63E+04	-2.55E+04	-2.2	-3.25	-59.1	-89.4	-0.176	-0.268
End of life	483	2.91E+04	13.5	31.4	-103	-22.3	-0.427	-0.306
Total	1.43E+05	1.95E+05	127	160	8.54E+03	1.05E+04	5.61	4.11

5 Assessment of the comparability of the systems

According to the ISO 14044 it is necessary that the equivalence of the systems is estimated[137]. Within both systems „the same functional unit and equivalent methodological considerations“[138] must be used. The equivalent methodological considerations concern for example performance, system boundary, data quality, allocation procedures, decision rules on evaluating inputs, and outputs impact assessment. In this LCA all mentioned aspects are equal.

Talking about the parameters the ISO prescribes to name all differences between them. In this LCA the parameters are all equal.

[137] DIN Deutsches Institut für Normung 2006
[138] ISO 14044

6 Life cycle interpretation

6.1 Identification of significant issues

According to the ISO standard 14044, structuring the results of the Life cycle inventory analysis and life cycle impact assessment phases is a component of a life cycle assessment and helps to determine the significant parameters[139]. Examples of significant issues are processes and productions which have a big influence on the overall result or a certain life section. The different life sections are divided into production, use phase and end of life. If you look first at the production, the battery and carbon fibre reinforced polymers are especially noticeable. Carbon fibre reinforced polymers has a big influence in the following categories (ADP, GWP, OPD, AP, FAETP and EP). The reason therefore is the high weight of carbon fibre reinforced polymers in the car.

The battery has mostly high values of 70% - 80% in all efficacy categories except ODP (see graphic for POCP, AP and EP). Steel shows striking values in both cars, the SunRiser and the blue.cruiser. Aluminium has a high value at ODP with about 46%.

The use phase is characterized by the positive influence on the environmental impact. This comes in the form of the feed in through the solar cell.

The end of life phase includes positive influences as well as negative influences on the environmental impact. If you consider the credits from the battery, aluminium and especially steel, you can say that the end of life phase generally has a positive influence, because almost all substances can be recycled. Only neodymium has a negative influence.

6.2 Consistency check

The consistency check should determine if the assumptions, the methods and data of our Life Cycle Assessment are consistent with the goal and scope.

As in the goal and scope stated (2.1 Goals), the aim of this LCA is a comparison between the thyssenkrupp SunRiser, built in 2015 and its successor the thyssenkrupp blue.cruiser, which is to be finalized in 2017. Main focus of this study is the sustainability of both cars and to what extent the blue.cruiser has improved compared to his predecessor. Furthermore, it enlightens the suitability for the everyday use of the SolarCars.

To achieve all assumptions, hotspots were chosen through a ABC-analysis, based on their weight in total or environmental impact. The chosen Hotspots then were analyzed with the Life-Cycle-Software GaBi and considered with regard to the chosen categories (2.2 Scope).

The data management was not equal, since most data of the SunRiser were already written down and there was almost no chance to review them again.

[139] Cf. DIN Deutsches Institut für Normung 2006

In contrast to that the data of the blue.cruiser were collected as soon as they were available. For this data collection, the LCA team worked in a dialogue with every single department team of the SolarCar, to achieve a maximum of transparency.

The Checklist below should give a good overview to the consistency of the data and methods.

Category	Possible Inconsistency	Comment
Data Source	SR. Data based on the records of the former team. BC. Data were collected as soon as they were available	The Data of the SR. were checked and reviewed again in cooperation with an expert of the SolarCar Team.
Data Accuracy	Limited software and information were used for collecting the data for the SR. Data of BC. were collected with newer Software and more information.	-
Data Age	Both data of the SolarCars were collected in the building period.	Workup of data of the SR as far as possible.
Software Used	SunRiser team had an older Version of the used Software than the blue.cruiser team.	-
Other Methods	Both Teams used the same Methods to achieve their data.	-
Categories	Both teams have used mainly the same categories to analyze the Hotspots.	-

Table 16: Consistency of data and methods

As the Checklist shows, there are slight signs of inconsistency, above all in the quality of the data processing (older version of GaBi vs. new full-version of GaBi) and the collecting of the information in general. Nevertheless, the current team has worked up the data of the SunRiser in cooperation with experts of the SolarCar Team as far as possible, to achieve a valuable transparency.
Additional to that both teams used similar or the same methods to collect, describe and to reappraise the collected information and data.

The little differences do not collide with the aims of the goals and scope, which were set beforehand. The result of the study shows a good transparency and meaningfulness in regard to the assumptions of the goal and scope.

6.3 Conclusions, limitations and recommendations

6.3.1 Conclusions

6.3.1.1 General

While analysing the scenarios and comparing blue.cruiser and SunRise are in most of the impact scenarios very similar (see table 10,11: impact assessment data). Differences can be perceived because of the seats inside the cars (see: Table 14: Data of impacts per person in comparison) and the total weight (see Table 18: ABC analysis SunRiser weight and Table 19: ABC analysis blue.cruiser weight). Another reason is using more steel (instead of CFRP) inside the blue.cruiser. Steel can be easily recycled and generate credits for environmental impacts. Another reason is to dump the SunRiser GaAs solar cell, because recycling is very difficult.
The lithium-ion battery dominates the impact categories POCP, AP, EP, HTP and FAETP (about 60%-80%). But there is not any lithium-ion battery impact in ODP, because the waste of CFRP can be recycled directly. Aluminium, Neodymium and CFRP are the most important materials for the ODP, the impacts of GWP are splitted into lithium-ion battery and CFRP. Steel is one of the deciding impacts of ADP (blue.cruiser), nearly completed by the lithium-ion battery and CFRP. Easy to see that steel is not a crucial factor for the SunRiser ADP impacts, because CFRP replaced most of the steel impacts inside the SunRiser.

6.3.1.2 Comparison

To show up the impacts of the thyssenkrupp blue.cruiser and thyssenkrupp SunRiser completely, every impact category can be compared with each other. While the SunRiser is fixed at 100%, the blue.cruiser reaches heavier impacts in 3 of 8 categories (see Figure 35: Impacts in comparison). Reason for higher impacts of ADP and FAETP is the weight of the blue.cruiser. These results contain information of the life cycle of the cars only, not the number of persons who can be carried.

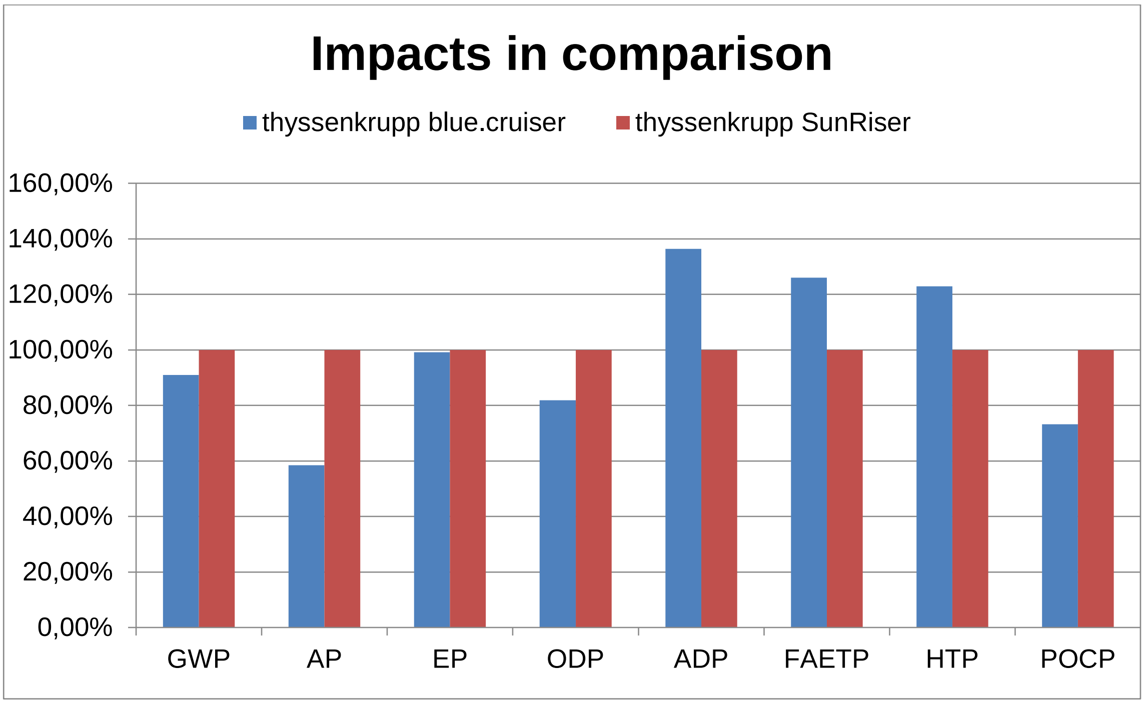


Figure 35: Impacts in comparison

Table 17: Data of impacts in comparison

Impact category	SunRiser	blue.cruiser
GWP	100%	91%
AP	100%	58%
EP	100%	99%
ODP	100%	82%
ADP	100%	136%
FAETP	100%	126%
HTP	100%	123%
POCP	100%	73%

While the SunRiser is able to carry two persons only, the impact results of the blue.cruiser can be split to four persons (unit: passenger km). Since it is the vision for the solar cars to operate this fully loaded in the car sharing business, it makes sense to consider passenger-kilometers. In case of carrying four persons inside the blue.cruiser, the impact results are much better than comparing the cars, only (see Figure 36: Impacts per person in comparison and Table 18: Data of impacts per person in comparison). Another positive side effect which declares the modelling results is a car boot with much more capacity inside the blue.cruiser.

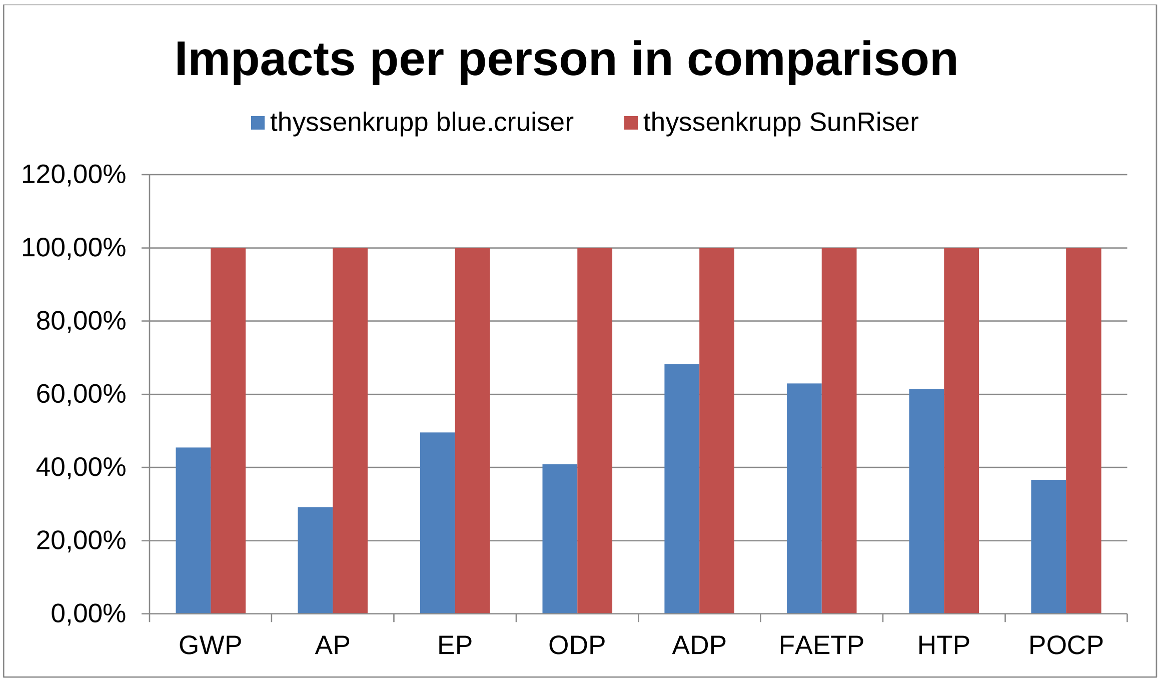
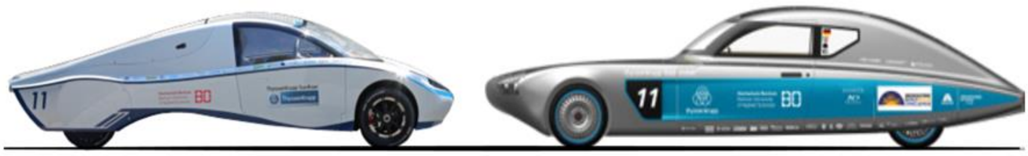


Figure 36: Impacts per person in comparison

Table 18: Data of impacts per person in comparison

Impact category	SunRiser (2 persons)	blue.cruiser (4 persons)
GWP	100%	45%
AP	100%	29%
EP	100%	50%
ODP	100%	41%
ADP	100%	68%
FAETP	100%	63%
HTP	100%	61%
POCP	100%	37%

Another way to compare both solar cars is the amount of steel installed inside the blue.cruiser. Using more steel instead of CFRP gets positive credits in environmental impacts, because of the recycling process of steel, and the less energy consuming manufacturing. Figure 35 shows the ecological influence of CFRP and steel components. By replacing CFRP with steel, the greenhouse gas potential of the material mix from the thyssenkrupp SunRiser was reduced from 22.4 kg CO2-eq. / kg to 19.3 kg CO2-eq. /kg in the thyssenkrupp blue.cruiser. This corresponds to a reduction of 14% in the steel and CFRP components.



CFRP share [kg]:	100.71	111.00
Steel share [kg]:	33.21	101.50
CFRP emissions [kg CO_2-eq.]:	2590	2860
Steel emissions [kg CO_2-eq.]:	410	1250
Emissions, total [kg CO_2-eq.]:	10300	9370
Share on total emissions [%]:	29%	44%
Emissions per kg CFRP / Steel mix [kg [kg CO_2-eq./ kg]:	**22.4**	**19.3**
Savings per material mix [%]:	**0%↓**	**-14%↑**

Figure 37: Environmental impact of CRFP and steel, own representation

Building a car using CFRP and NFRP (blue.cruiser), the environmental impacts are much better than using CFRP, only. The impact of using one kilogram CFRP is 29.67 kg CO2-eq, one kilogram of NRFP produces 22.82 kg CO2-eq (see Table 120: ABC analysis SunRiser weight and Table 121: ABC analysis blue.cruiser weight).

6.3.1.3 Comparison with conventional cars

Since a solar car is street legal and has similar equipment as conventional cars, the following table compares the environmental impacts of solar-powered vehicle and cars. It should be noted that LCA studies are not completely comparable, because of different objectives and system delimitations; also, a SolarCar is a prototype, which is distinguished by the dimensions, design and costs from conventional cars. Table 19 compares life cycle data of different vehicle types:

Table 19: LCA data of different cars

Vehicle	Engine	Production [kg CO2-eq.]	Use [kg CO2-eq.]	End of life [kg CO2-eq.]	Total [kg CO2-eq.]
thyssenkrupp SunRiser[1]	electric	12060	-1570	-735	10300
thyssenkrupp blue.cruiser[1]	electric	12400	-2470	-560	9370
Mercedes-Benz B-Class	electric	10800	12480	720	24000
Mercedes-Benz C-Class	Plug-In hybride	7200	28080	720	36000
Renault Espace	gasoline	7400	21300	750	29450
Renault Twingo	gasoline	4600	17585	380	22565
VW Golf IV	gasoline	4400	25330		29730

[1]Only hotspots are considered (86% weight share)

6.3.2 Limitations

- It was just looked at the chosen Hotspots and not all installed materials.
- The Hotspots were chosen, based on weight in total and influence on environmental matters.
- With just regarding the Hotspots, about 86% (see Table 1: ABC analysis SunRiser weight and Table 2: ABC analysis blue.cruiser weight) of the blue.cruiser was covered by this study.
- Additional assumptions were made regarding the triple junction GaAs solar cell model. It is based on the silicon solar cell model because of limited data management. For the recycling no further information were found, so an assumption was made, that the triple junction GaAs solar cell is deposited.
- Other limitations in data management are the restricted information about ROHACELL®, because it is a product developed by Evonik.
- Neodymium could not be accounted for ADP because of missing information.
- In the GaBi model of NFRP a conventional epoxy system was used. There was no similar process to show the biological share in the epoxy system from Sicomin.

6.3.3 Recommendations

6.3.3.1 CFRP – NFRP comparison

To proof that the use of NFRP has a positive impact on the environment, a scenario was created. In this scenario, no NFRP was installed in the blue.cruiser.
To compare NFRP with CFRP it is to mentioned, that NFRP weighs twice as much as CFRP. Additional, the energy consumption during the production is the same for both materials because of the same manufacturing process.
The fact that NFRP is rigid and not that elastic compared to CFRP, led to the decision of the SolarCar team to build smaller components like the dashboard, centre console and the interior door of NFRP. In this scenario, the NFRP amount in the blue.cruiser was converted to the same assumed amount of CFRP. Furthermore, the new weight of CFRP (6 kg) was added to the weight, which was used for real (111 kg). A model was built in GaBi with a weight of CFRP of 117 kg and no amount of NFRP.

The figure below shows the comparison of the two models:

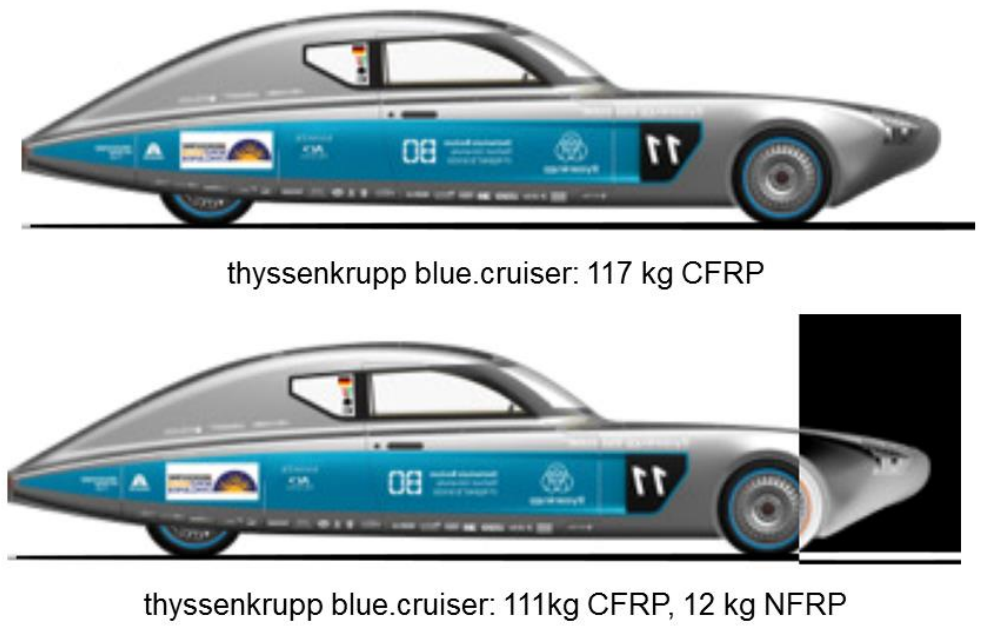


Figure 38: Comparison CFRP versus NFRP

The next table shows up the environmental impacts of the NFRP-CFRP combination and a special CFRP model using the same weight. In addition, the results are presented in bar charts underneath (see figure 1-8).

Table 20: Results of using only CFRP

Impact category	CFRP and NFRP	CFRP (model)
ADP	34200 MJ	76200 MJ
GWP	2560 kg CO2-eq	6600 kg CO2-eq.
ODP	-0.000002 kg R11-eq.	-0.000003 kg R11-eq.
POCP	0.37 kg ethene-eq.	0.83 kg ethene-eq.
AP	3.8 kg SO2-eq.	9.8 kg SO2-eq.
EP	0.7 kg phosphate-eq.	1.7 kg phosphate-eq.
HTP	80 kg DCB-eq.	212 kg DCB-eq.
FAETP	6.4 kg DCB-eq.	11.7 kg DCB-eq.

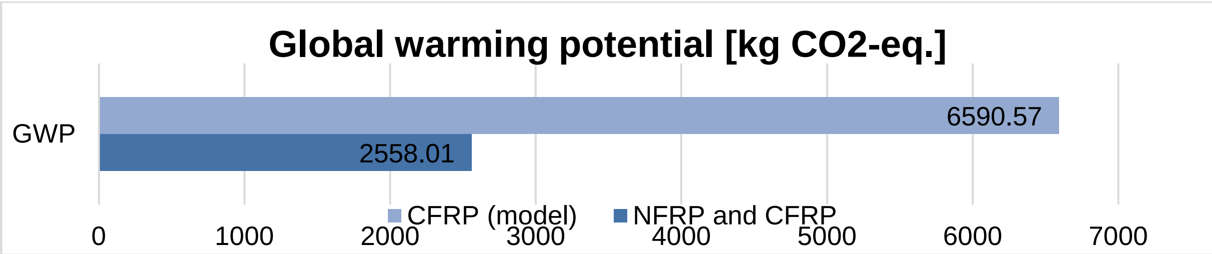


Figure 39: GWP comparison with CFRP model

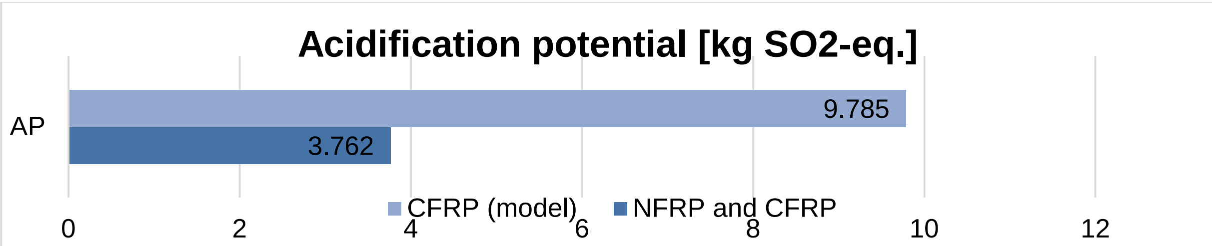


Figure 40: AP comparison with CFRP model

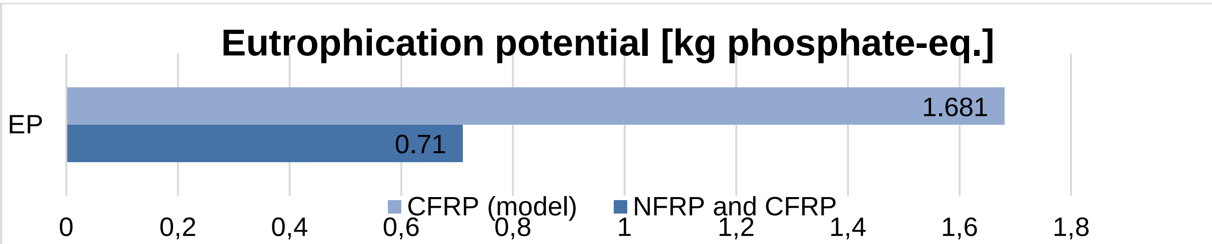


Figure 41: EP comparison with CFRP model

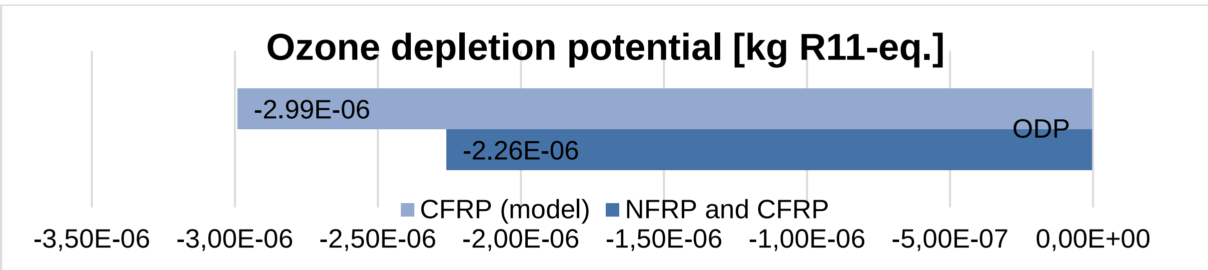


Figure 42: ODP comparison with CFRP model

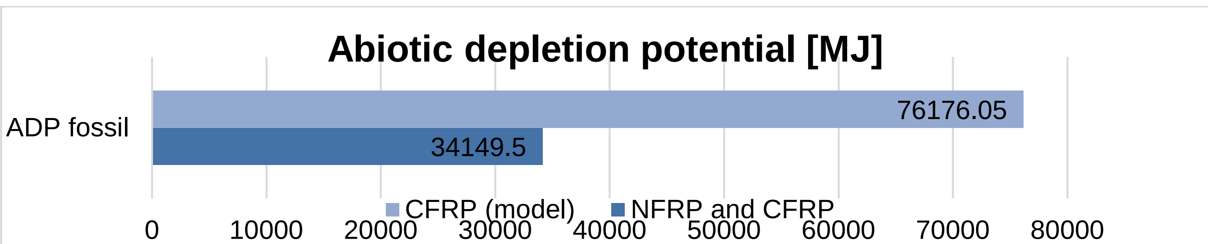


Figure 43: ADP comparison with CFRP model

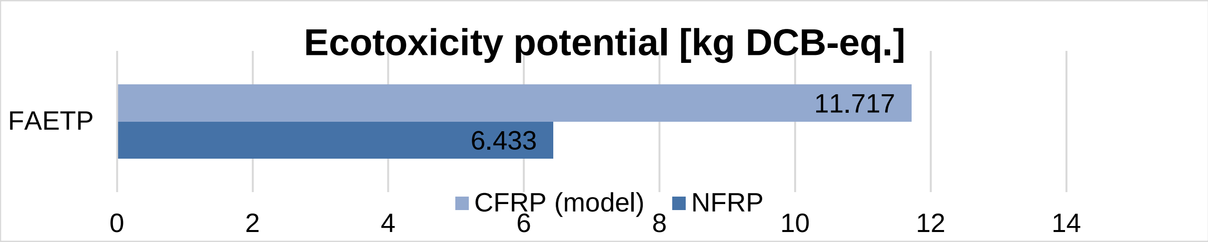


Figure 44: FAETP comparison with CFRP model

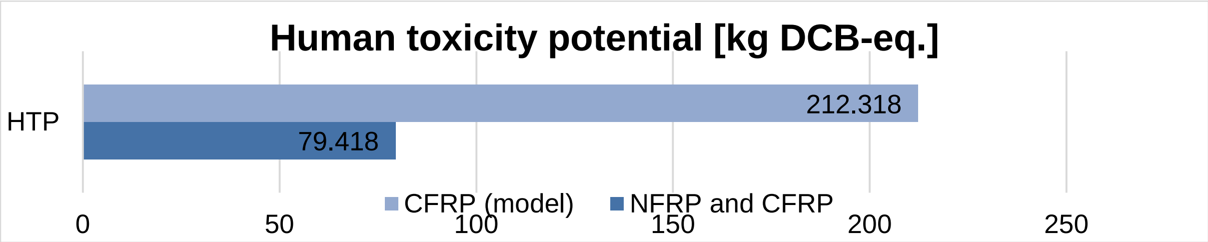


Figure 45: HTP comparison with CFRP model

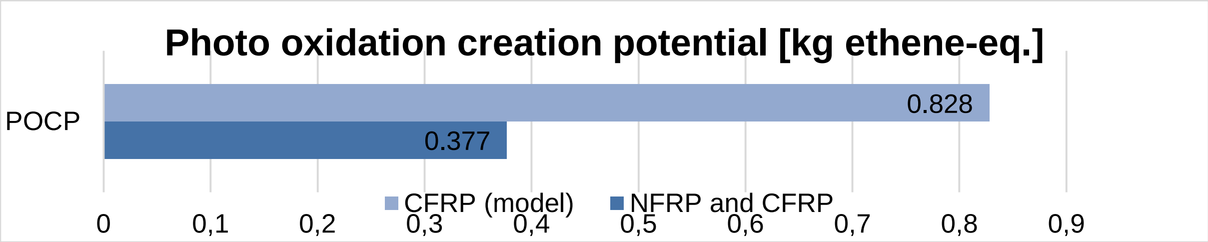


Figure 46: POCP comparison with CFRP model

As shown in the bar charts, the use of NFRP has a better impact on the environment compared to the use of CFRP. The only negative impact of this scenario is shown in the category of ODP. The reason for that negativity is, that NFRP has a higher amount of waste material (clipping) which is thermal combusted. So CFRP comes off well in the category of ODP compared to NFRP. The impacts are always reducing up to 40% of the impact.

In conclusion it is to mention, that the use of NFRP instead of CFRP is reasonable, especially in regard of the environmental impact. This shows that an expanded utilization of NFRP could be a further improvement for upcoming future projects.

6.3.3.2 Reduction of aluminium scrap

By manufacturing or shaping some of the materials for the SolarCars a lot of waste in the form of scrap accumulates. Notable materials are for example Plexiglas, steel, nickel and especially aluminium. Most components made out of aluminium are milled, which results in scrap of 97.18% for the thyssenkrupp blue.cruiser. This means that out of 1264.72 kg aluminium only 36.7 kg are effectively used in the SolarCar.

To see which effect, it could have on the Lice Cycle Inventory Analysis (LCA / LCIA) of the SolarCars if the scrap would be reduced, additional calculations with varying degrees of scrap using the example of aluminium have been created.

As seen in Figure 47: Reduction of aluminium the reduction of waste by only approximately 7% lessens nearly every impact category by half or more. Especially the ozone depletion potential (ODP), but also the global warming potential (GWP) and abiotic depletion potential (ADP) shows sizable differences. The impact category however, in which it would be preferable to notice a high change in value, the human toxicity potential (HTP), shows the smallest decrease of all categories with a reduction of only 16% to its original state.

To get completely rid of any scrap would naturally be the most desired scenario, because it would ensure the lowest possible value of each impact category. This however requires that all components are produced through additive manufacturing, which at this point of time is not viable for mass production.

As Figure 47 shows, the decrease of each impact category is at its highest, when the reductions of scrap are relatively minor. At a certain point, the value of the impact categories reaches nearly a constant. As a result, the production of components does not need to be completely scrap-free. It suffices if the waste is reduced to around 70% of the used material.

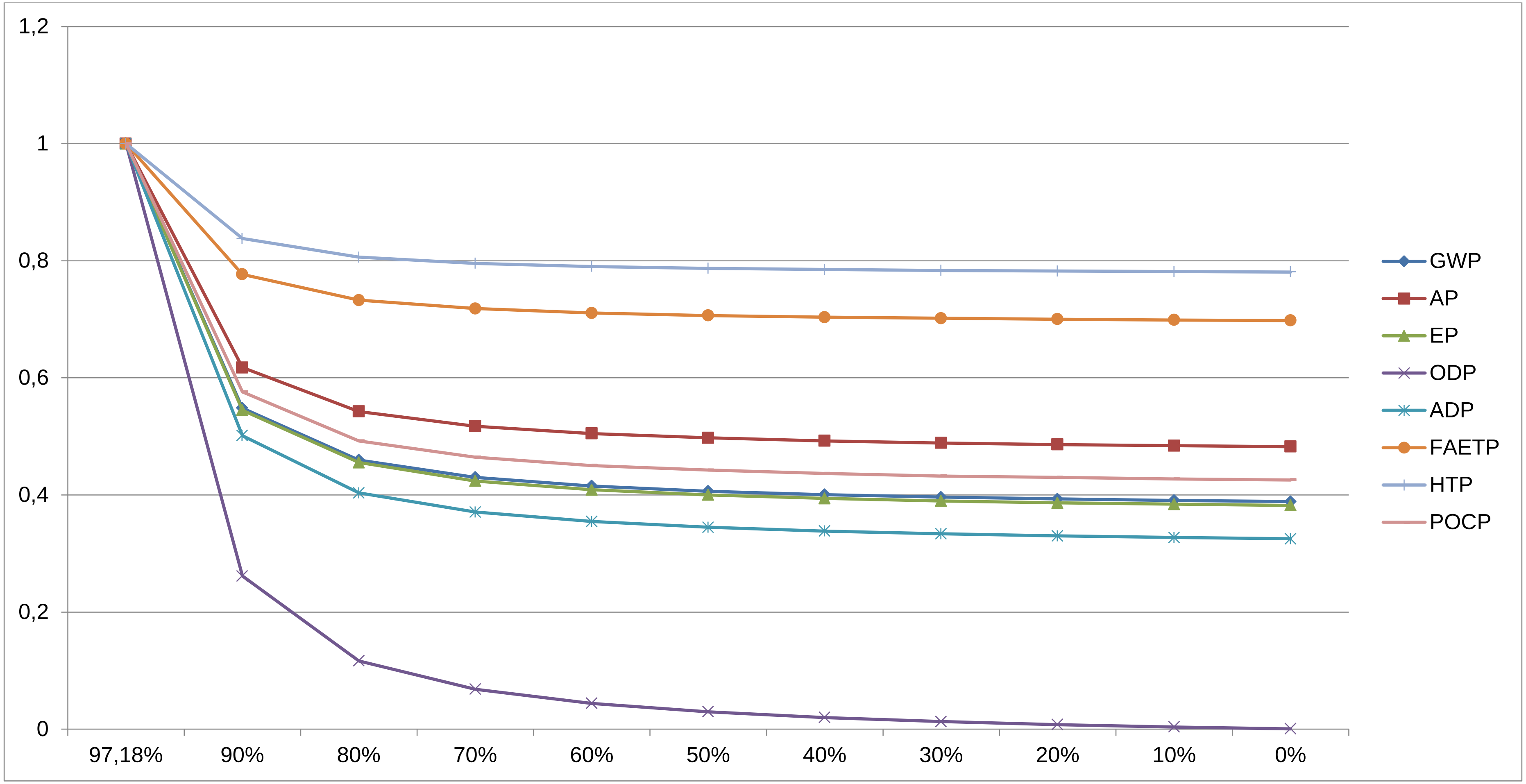


Figure 47: Reduction of aluminium scrap

Table 21: Results of reduction of aluminium scrap

scrap	GWP	AP	EP	ODP	ADP	FAETP	HTP	POCP
97.18%	916.12	2.717	0.2350	5.93E-06	11801.5	3.18	1388.8	0.1910
90%	502.38	1.678	0.1280	1.55E-06	5917.4	2.47	1163.8	0.1100
80%	421.13	1.474	0.1070	6.91E-07	4761.9	2.33	1119.6	0.0940
70%	394.05	1.406	0.0996	4.05E-07	4376.8	2.29	1104.8	0.0887
60%	380.51	1.372	0.0961	2.61E-07	4184.2	2.26	1097.5	0.0860
50%	372.38	1.352	0.0940	1.76E-07	4068.6	2.25	1093.1	0.0845
40%	366.97	1.338	0.0926	1.18E-07	3991.6	2.24	1090.1	0.0834
30%	363.10	1.328	0.0916	7.73E-08	3936.6	2.23	1088.0	0.0826
20%	360.20	1.321	0.0908	4.66E-08	3895.3	2.23	1086.4	0.0821
10%	357.94	1.315	0.0903	2.28E-08	3863.2	2.23	1085.2	0.0816
0%	356.13	1.311	0.0898	3.66E-09	3837.5	2.22	1084.2	0.0813

7 Key messages

1. Through intelligent material use, i.e. to use steel where it is useful (grid frame), the greenhouse gas emissions were reduced by 14% (see Figure 37: Environmental impact of CRFP and steel, own representation.
2. Due to the full potential of the possible riders, the environmental impact of the thyssenkrupp blue.cruiser per head was significantly reduced (45%, see Table 18: Data of impacts per person in comparison).
3. Comparing conventional cars and solar cars, more than double emissions are caused during the entire lifecycle by a conventional car (see Table 19: LCA data of different cars; the present study considers only hotspots).
4. A solar-powered vehicle is an energy-positive vehicle that generates more electrical energy than it consumes in its use (see Usage scenario).
5. Electrical cars have low emissions in the utilization phase, most emissions are released during production (see Table 19: LCA data of different cars). The biggest correcting variable is the electrical energy storage / battery (see Table 14: Impact assessment data (1), Table 15: Impact assessment data (2)).
6. The intelligent material implementation of natural fibers offers high potential to reduce the environmental impact of a product (see Table 20: Results of using only CFRP).
7. The reduction of waste and the increased use of standard parts / serial parts can not only reduce the production costs, but also has a huge impact on the environmental footprint (see Table 21: Results of reduction of aluminium scrap).

8 LITERATURE

WBGU. (2013). *Politikberatung zum Globalen Wandel: Keine Entwicklung ohne Umweltschutz: Empfehlungen zum Millennium+5-Gipfel – Politikpapier.* Berlin: WBGU.

WBGU. (2013). *Welt im Wandel: Menschheitserbe Meer – Hauptgutachten.* Berlin: WBGU.

Abts, G. 2007, *Einführung in die Kautschuktechnologie*, München.

AGPU e.V. 2016, *Alles über PVC: Von der Herstellung bis zum Recycling*, Bonn, https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwiGzP_L8I_TAhWDvBoKHRIhA4wQFggaMAA&url=http%3A%2F%2Fwww.agpu.de%2Fwp-content%2Fuploads%2F2016%2F03%2FAGPU_AllesueberPVC_DE.pdf&usg=AFQjCNGo6Z3BPu57-yy9GtJX93Wz69DOGw&sig2=dRF5FjaK9UYrKP6IUddE4Q&bvm=bv.152174688,d.d2s&cad=rja.

Aitor P. Acero, Cristina Rodríguez, Andreas Ciroth 2016, *LCIA methods*, http://www.openlca.org/wp-content/uploads/2016/08/LCIA-METHODS-v.1.5.5.pdf.

Alger, M.S.M. 1997, *Polymer science dictionary*, London.

Amarakoon, S./J. Smith/B. Segal 2013, *Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles*.

Andreas Theuer 2016, *Umwelt- und Klimaschutz*, https://www.thyssenkrupp-steel.com/de/unternehmen/nachhaltigkeit/umwelt-und-klimaschutz/umwelt-und-klimaschutz.html.

Associates, F./Genan 2010, *Comparative Life Cycle Assessment of Two Options for Scrap Tire Treatment - Material Recycling Vs. Tire-derived Fuel Combustion*.

AZO Materials 2012, *Magnesium AZ31B Alloy (UNS M11311)*, www.azom.com/article.aspx?ArticleID=6707.

Biederbick, K. 1983, *Kunststoffe* (Vogel-Fachbuch), Würzburg.

bre 2005, *Green Guide to Specification: BRE Materials Industry Briefing Note 3a: Characterisation*, http://www.bre.co.uk/greenguide/files/CharacterisationBriefingDocumentFinal.pdf.

breglobal, *Ecotoxicity: Ecotoxicity to freshwater and land*, https://www.bre.co.uk/greenguide/page.jsp?id=2099.

Buchert, M./J. Sutter 2015, *Ökobilanzen zum Recyclingverfahren LithoRec II für Lithium-Ionen-Batterien*, Berlin, Darmstadt.

CHEMIE.DE Information Service GmbH, *Magnesium*, http://www.chemie.de/lexikon/Magnesium.html.

CHEMIE.DE Information Service GmbH, *Stahl*, http://www.chemie.de/lexikon/Stahl.html.

Data sheet: Triple Junction GaAs Solar Cell: Type: TJ Solar Cell 3G28C 2016.

Detzel, A./J. Giegrich/M. Krüger/S. Möhler/A. Ostermayer 2004, *Ökobilanz für PET-Einwegsysteme unter Berücksichtigung der Sekundärprodukte: Endbericht*. erstellt für PETCORE, Heidelberg.

Deutsches Kupferinstitut Berufsverband e.V. 2017a, *Analysis for copper products*, https://www.kupferinstitut.de/de/werkstoffe/system/life-cycle-kupfer/analysis-for-copper-products.html.

Deutsches Kupferinstitut Berufsverband e.V. 2017b, *Cu-ETP: Werkstoff Datenbank*, https://www.kupferinstitut.de/fileadmin/user_upload/kupferinstitut.de/de/Documents/Shop/Verlag/Downloads/Werkstoffe/Datenblaetter/Kupfer/Cu-ETP.pdf.

Deutsches Kupferinstitut Berufsverband e.V. 2017c, *Herstellung von Kupfer*, https://www.kupferinstitut.de/de/werkstoffe/system/herstellung-kupfer.html.

Deutsches Kupferinstitut Berufsverband e.V. 2017d, *Kupfer Erze*, https://www.kupferinstitut.de/de/persoenlicheberatung/kupfer-wiki/details/article/kupfer-erze.html.

DIN Deutsches Institut für Normung 2006, Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen.

Dr. Heinz Eickenbusch, Dr. Oliver Krauss 2013, *Kohlenstofffaserverstärkte Kunststoffe im Fahrzeugbau: Ressourceneffizienz und Technologien*.

EEM Energy & Environment Media GmbH i.Gr., *Aktuelle Sonneneinstrahlung: Sonneneinstrahlung Deutschland*, http://www.solarserver.de/service-tools/strahlungsdaten/deutschland.html.

Ellingsen, L.A.-W./G. Majeau-Bettez/B. Singh/A.K. Srivastava/L.O. Valøen/A.H. Strømman 2014, Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack, *Journal of Industrial Ecology* 18, 113–124.

EPD International AB, *Characterisation factors for default impact assessment categories*, http://www.environdec.com/en/The-International-EPD-System/General-Programme-Instructions/Characterisation-factors-for-default-impact-assessment-categories/.

European Commission 2004, *Life Cycle Assessment of PVC and of principal competing materials*, https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjOsbuG84_TAhVGVRoKHdy3DjwQFggdMAA&url=http%3A%2F%2Fwww.envirocentre.ie%2Fincludes%2Fdocuments%2Fpvc-final_report_lca.pdf&usg=AFQjCNE-bASvT_ZmpI4tfc_0I8KWpg7akg&sig2=HkVfBWdQ2FopzUCw5RlODg&bvm=bv.152174688,d.d2s.

European Copper Institute 2012, *The environmental profile of copper products: A ‘cradle-to-gate‘ life-cycle assessment for copper tube, sheet and wire produced in Europe*, Brüssel, https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwi8neeV-Y_TAhVGwxQKHcvzAM0QFggaMAA&url=http%3A%2F%2Fcopperalliance.eu%2Fdocs%2Fdefault-source%2Fresources%2Fthe-env-profile-of-copper-prod-

ucts_lifecycle.pdf%3Fsfvrsn%3D2&usg=AFQjCNEL1rSHoByPbOvUy9eSRJ_AIt4ghg&sig2=kVXJVqT34GLzaw1SWJOIgA&bvm=bv.151426398,d.d24.
EVONIK 2015, *Plexiglas im Automobilbau*, www.plexiglas-polymers.de/sites/lists/PM/DocumentsAP/511-2-Automobilbau-de.pdf.
Evonik Resource Efficiency GmbH, *About ROHACELL®: Environment and safety*, http://www.rohacell.com/product/rohacell/en/pages/company-information.aspx.
Evonik Resource Efficiency GmbH 2015, *Product Information for Safe Use: ROHACELL®*, http://www.rohacell.com/sites/lists/RE/DocumentsHP/ROHACELL-product-information-for-safe-use-EN.pdf.
Fachagentur Nachwachsende Rohstoffe e. V., *Naturfaserverstärkte Kunststoffe: Pflanzen, Rohstoffe, Produkte*, http://www.nova-institut.de/pdf/06-02_FNR-NFK-nova.pdf.
Feraldi, R./S. Cashman/M. Huff/L. Raahauge 2013, Comparative LCA of treatment options for US scrap tires: Material recycling and tire-derived fuel combustion, *Int J Life Cycle Assess* 18, 613–625.
FIZ Karlsruhe – Leibniz-Institut für Informationsinfrastruktur GmbH 2006, *Energieintensive Branchen: Daten zu besonders energiehungrigen Produktionsbereichen*, http://eneff-industrie.info/quickinfos/energieintensive-branchen/daten-zu-besonders-energiehungrigen-produktionsbereichen/.
Fraunhofer 2012, *Leichtbau in Mobilität und Fertigung: Ökologische Aspekte*, http://www.e-mobilbw.de/de/service/publikationen.html?file=files/e-mobil/content/DE/Publikationen/PDF/Leichtbau-Studie-Oekologische-Aspekte-150.pdf.
Frieder Braun 2012a, *Herstellung einer Silizium Solarzelle*.
Frieder Braun 2012b, *Herstellung einer Silizium-Solarzelle*.
GaBi: Product Sustainability Performance 2017.
Giti Tire, *Tire Production Process - Meticulous and Complex*, http://www.giti.com/images/newsdetailattach_20128194115667.pdf.
Gladden, C./E. Kim/Z. Lin/M. Ulmefors/D. Dornfeld/M. Hutchins 2012, *Life Cycle Assessment of Photovoltaic Modules*, Berkeley.
Gooch, J.W. (ed.) 2007, *Encyclopedic Dictionary of Polymers*, New York, NY.
Institut für seltene Erden und Metalle 2016, *Aktuelle und historische Marktpreise der Seltenen Erden und strategischer Metalle*, http://institut-seltene-erden.org/aktuelle-und-historische-marktpreise-der-gangigsten-seltenen-erden/.
Jennifer E. Granata, J.H.E.P.H.M.H.R.R.K.D.D.K., *Conference record of the Twenty-Eighth IEEE Photovoltaic Specialists Conference - 2000: Anchorage Hilton Hotel, Anchorage, AK, 15 -22 September 2000*, Piscataway, NJ.
Jens Wieberneit 2015, *Erfassung und Verwertung von Windenergieanlagen: Bachelorarbeit*.
K&J Magnetics, *How Sintered Neodymium Magnets are Made*, https://www.kjmagnetics.com/blog.asp?p=how-neodymium-magnets-are-made.
Klöpffer, W./B. Grahl 2009, *Ökobilanz (LCA): Ein Leitfaden für Ausbildung und Beruf*, Weinheim.
Korthauer, R. 2013, *Handbuch Lithium-Ionen-Batterien*, Berlin, Heidelberg.

LEDVANCE GmbH, *Environmental Impact Categories*, https://www.ledvance.com/company/sustainability/environmental/product-lifecycle-management/method-and-definitions/environmental-impact-categories/index.jsp.

Magontec Group, *Mg-Legierung & Recycling: Magontec - Spezialist im Recycling und in der Herstellung von Magnesiumlegierungen*, http://magontec.com/de/products-services/recycling/.

Marilyn Minus, S.K., The processing, properties, and structure of carbon fibers, in *JOM*, 52–58.

Matthias Achternbosch 2002, *Material flow analysis: A comparison of manufacturing, use and fate of CFRP - Fuselage components versus aluminium-components for commercial airliners*.

Matthias Buchert/Jürgen Sutter 2015, *Ökobilanzen zum Recyclingverfahren LithoRec II für Lithium-Ionen-Batterien*, Berlin, Darmstadt.

Matthias Dienhart, *Ganzheitliche Bilanzierung der Energiebereitstellung für die Aluminiumherstellung*, Aachen.

Mertens, K. 2014, *Photovoltaics: Fundamentals, technology and practice*, Chichester.

Michael Karus 2006, *Naturfaserverstärkte Kunststoffe (NFK)*, http://www.nova-institut.de/pdf/Road-Show-Broschuere.pdf.

Mirja Beste 2016, *Aufbau und Funktionsprinzip der Silizium Solarzelle: Woraus besteht eine Silizium-Solarzelle? Wie wird sie hergestellt? Wie erzeugt man mit Silizium Solarstrom?*, 2014, http://www.energie-experten.org/erneuerbare-energien/solarenergie/solarzelle/silizium-solarzelle.html.

Muster, F. 2007, *Rotschlamm: Reststoff aus der Aluminiumoxidproduktion-- Ökologischer Rucksack oder Input für Produktionsprozesse?* (Entwicklungsperspektiven Nr. 88), Kassel.

N. J. Mohr, J. J. Schermer, M. A. J. Huijbregts, A. Meijer, L. Reijnders 2007, *Life cycle assessment of Thinfilm GaAs and GaInP/GaAs solar modules*.

National Center for Biotechnology Information, *Methyl methacrylate: PubChem Compound Database*, https://pubchem.ncbi.nlm.nih.gov/compound/6658.

Norddeutscher Rundfunk 2011, *Das schmutzige Geheimnis sauberer Windräder*, http://daserste.ndr.de/panorama/archiv/2011/windkraft189.html.

norelem Normelemente KG n.d, *Product Information Sheet: 03089 Arretierbolzen kurze Ausführung*, Markgöningen.

Norman, D.T., *What is Carbon Black? Rubber grades from carbon black*, Houston, http://www.continentalcarbon.com/what-is-carbon-black.asp.

Notter, D.A./M. Gauch/R. Widmer/P. Wager/A. Stamp/R. Zah/H.-J. Althaus 2010, Contribution of Li-ion batteries to the environmental impact of electric vehicles, *Environmental science & technology* 44, 6550–6556.

Nowak, S. (ed.) 2012, *Proceedings / EU PVSEC 2012, 27th European Photovoltaic Solar Energy Conference and Exhibition: Messe Frankfurt and and Congress Center, Frankfurt, Germany, Conference 24 - 28 September 2012, Exhibition 25 - 28 September 2012*, München.

Nuss P, E.M.J. 2014, *Life Cycle Assessment of Metals: A Scientific Synthesis*, http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0101298.
Panasonic Industrial Company 2015, *Product Information Sheet: Lithium-ion Batteries (Li-ion)*, Rolling Meadows, Illinois.
PlasticsEurope 2012, *Long and Short-chain Polyether Polyols for Polyurethane Products: Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers*. ISOPA.
Product Information Sheet: MAXEON™ GEN III SOLAR CELLS 2015, San José, California.
R. R. King, N.H.K.J.H.E.M.H.P.C.T.I.H.Y.H.L.C.D.E.J. 2000, *Next – Generation, high-efficiency 3-4 multijunction solar cells*, Spectrolab, Inc., 12500 Gladstone Ave., Sylmar, CA 91342.
Robert Doelling 2013, *Slarmodule: So funktioniert das Recycling*, http://de.solarcontact.com/blog/2013/05/solarmodule-funktioniert-das-recycling/.
Rudolf Vetsch, C.L. 2016, *Material Archiv: Aluminium ZnMg-Knetlegierung. EN AW-7075*, http://www.materialarchiv.ch/materialarchiv/ws/helper/specsheet.php?id=1305.
Sebastian Nöll 2010, *Carbon Composite: Kohlefaserverbundwerkstoffe*, http://fachinfo.bistech.de/artikel/790/Carbon+Composite+(CFK)+-+Kohlefaserverbundwerkstoffe.
Sicomin Epoxy Systems 2014, *Bio based epoxy*, http://www.sicomin.com/products/epoxy-systems/bio-based-epoxy.
SolarCar Battery-Team 2016, *Battery Component List*.
SolarCar Team 2015 2017, Hochschule Bochum.
SolarCar Team 2016 2017, Hochschule Bochum.
Sprecher, B./Y. Xiao/A. Walton/J. Speight/R. Harris/R. Kleijn/G. Visser/G.J. Kramer 2014, Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets, 3951–3958.
SunPower 2015, *Product Information Sheet: MAXEON™ GEN III solar cells*, San José, California.
Supermagnetic 2015, *Herstellung von Neodym Magneten: Verfahren zur Herstellung von Neodym-Eisen-Bor-Magneten*, https://supermagnetic.de/herstellung-neodym-magnete/.
ThyssenKrupp Magnettechnik, *Neodym-Eisen-Bor-Magnete*, http://www.thyssenkrupp-magnettechnik.com/index.php/neodym-eisen-bor-magnete.html.
VDI Verlag GmbH 2014, *Magnet-Rohstoff Neodym: China will nicht nur liefern, sondern verarbeiten: Branche fürchtet neues Monopol*, http://www.ingenieur.de/Branchen/Rohstoffindustrie/Magnet-Rohstoff-Neodym-China-liefern-verarbeiten.
ViPER Group n.d, *Research: The Lithium-ion Battery*, https://engineering.purdue.edu/ViPER/research.html.
Werkstoff-Datenblatt: EN AW-7075 (Al Zn5,5MgCu).

Wirtschaftsvereinigung Stahl, *Roheisen- und Rohstahlerzeugung*, http://www.stahl-online.de/index.php/themen/stahltechnologie/stahlerzeugung/.
Wortmann, C./F. Dettmer/F. Steiner 2013, Die Chemie des Reifens: Mehr als schwarz und rund, *Chemie in unserer Zeit*.
ZEIT ONLINE GmbH 2012, *Karosserie statt Komposthaufen: Günstige Alternative zu Carbon*, http://www.zeit.de/auto/2012-08/leichtbau-meerrettich/seite-2.