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Life Cycle Assessment of Body-in-White Produced from Recycled Aluminum

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Nanotechnology	
Submission date:	August 2014
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Declaration

I hereby declare that except for references cited and duly acknowledged, the views expressed here are the product of my own research.

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Acknowledgements

This master thesis, done spring 2014 is a part of the Masters degree in Nanotechnology, with specialization in Materials, Energy and the Environment, as well as Industrial Ecology.

I would like to thank my supervisors Johanne Hammervold at MiSA AS and Ragnhild Elizabeth Aune at Department for Material Science and Engineering for their good support and useful feedback.

I would also like to thank Snorre Kjørstad Fjeldbo at Hydro ASA, and Johan Pettersen at MiSA AS for helping me with the shaping of this project and for useful feedback during the work.

Finally, I would also like to thank my family and friends for their support and help during the writing of this project.

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Abstract

The secondary production of aluminum has a large potential in terms of energy savings compared to primary production. Due to the increasing use of aluminum in products, there is a larger demand for aluminum than can be covered by secondary aluminum only. Today, most aluminum that reach end of life treatment is down-cycled. In the future the amount of available scrap will grow larger, and more secondary aluminum will become available for recycling. This gives motivation for closing recycling loops and minimize down-cycling. An investigation of the need for scrap sorting and refining is necessary, and the environmental impacts of the applied technologies should be examined. A suitable tool for doing this is an Life Cycle Assessment (LCA).

The goal of the present study is to compare the environmental performance for an aluminum Body-in-White (BiW) made from three different material inputs, *i.e.* primary aluminum, closed-loop recycled old BiWs and open-loop recycled end of life vehicle (ELV) scrap. This is done by performing an LCA. The challenges and benefits of switching from primary to secondary aluminum is enlightened.

Based on the results found in the present study it is clear that scrap is the best input choice, in terms of environmental performance. However, large challenges with input data to the LCA model affects the quality of the results. It is reasonable to assume that the difference between the impact for the three scenarios will change if all inputs where added.

The current project also discusses several aspects and challenges regarding the use of scrap as input to BiWs. This is necessary as the project is based on assumptions and projections on what the future might look like. First, the challenges of availability of suitable scrap. Second, the challenge of scrap economy and how this varies with time and politics. Third, the challenge of sufficient treatment of the scrap for obtaining an acceptable quality.

Sammendrag

Sekundærproduksjon av aluminium har et stort potensial for energibesparelser sammenlignet med primærproduksjon. På grunn av den økende bruken av aluminium i produkter, er det per dags dato et større behov for aluminium enn det som kan møtes av kun sekundærproduksjon. Det meste av aluminium som resirkuleres brukes til produkter med lavere krav til renhet. I framtiden vil skrapmengden bli større, og mer sekundær aluminium vil derfor bli tilgjengelig for resirkulering. Dette motiverer til å lukke resirkuleringssløyfer og minimere degradering. For å kunne gjøre det trengs det undersøkelser av skrapsorterings-teknologier og raffineringsteknologier, samt miljøpåvirkningen av disse. Livsløpsanalyse er et egnet verktøy for dette.

Målet med dette prosjektet er å sammeligne miljøpåvirkningen for en aluminiums Body-in-White (BiW) laget av tre ulike materialer. Disse tre materialene er; primæraluminium, sekundæraluminium fra gamle BiW og sekundæraluminium fra bilskrap. Dette gjøres ved å utføre en LCA. Utfordringene og fordelene med å bruke sekundæraluminium i stede for primæraluminium belyses.

Resultatene i dette prosjektet viser at sekundæraluminium er det beste valget, sett i lys av miljøpåvirkning. A finne god data til livsløpsanalysen for dette prosjektet viste seg å være utfordende, og dette påvirker kvaliteten på resultatene. Det er sannsynlig at forskjellen mellom de tre senarioene ville endret seg dersom bedre data hadde vært tilgjengelig.

Prosjektet diskuterer også flere aspekter og utfordringer med bruken av sekundæraluminium i BiW. Dette er nødvendig fordi prosjektet baseres på antagelser om hvordan framtiden vil se ut. Først diskuteres utfordringene rundt skraptilgjengelighet, deretter diskuteres skrapøkonomi og hvordan den varieres med tid og politikk. Sist diskuteres utfordringen med behandling og raffinering av skrap for å oppnå en tilfredstillende kvalitet.

Contents

The picture on the front cover shows the car Audi A2 [1].

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Glossary

Allocation - A method for sharing the environmental loads when several products/functions shares processes and data is not found for the individual products.

Body in white (BiW) - The term used for the structural car part which consists of metal welded together. It is before painting, and any moving parts like doors is added. No motor, electrical components, glass or seats etc.

Cast alloys - Alloys that are produced by pouring liquid aluminum into a mold to give the desired shape. Cast alloys have lower purity requirements than wrought alloys.

Closed-loop recycling - A used product is recycled back to the same product.

Cut-off Approach - To account for the recycling in a products life cycle at the beginning of life, as input material for production.

Down-cycling - A used product is used in a new product with lower requirements in terms of chemical composition and performance. Also called open-loop recycling.

Eddy current separation - A sorting technique that uses the variations in conductivity for metals to separate metal scrap.

Electro magnetic separation - A sorting technique that separates ferrous and non-ferrous scrap by the use of magnets.

End of life (ELVs) vehicles - Vehicles that have reach their end of life, and no longer are in use.

Extrusion - Wrought semi-manufacturing technique for aluminum products.

Foundry - The place where liquid aluminum is shaped into products by casting.

Gas metal welding - A welding technique where the weld area is shielded by an external gas to avoid contamination of the surface.

Global warming potential (GWP) - A measure of how much heat a greenhouse gas traps in the atmosphere. It is calculated over a specific time interval, 20, 100 or 500 years.

High-end product - A product that has strict requirements regarding performance and therefore also chemical composition of the materials used.

Hydroforming - An extrusion technique that uses fluid pressure to shape the material into desired shape.

Laser-induced breakdown spectroscopy - Alloy-specific sorting technique that uses laser spectroscopy to analyze and sort scrap.

Laser welding - A welding technique that uses a laser to join two metals together.

Life cycle assessment (LCA) - A method for assessing the environmental impacts from all stages in a product life cycle.

Metal-inert gas (MIG) welding - A gas metal arc welding technique, where the shielding gas is inert.

Modulus of elasticity - A material property that describes stiffness, or a materials tendency to deform.

Open-loop recycling - A discarded product that is used as a raw material for a new product of a different kind. Involves a change of properties. Also called down-cycling.

Primary aluminum - Aluminum that is extracted from raw material trough mining of minerals and further processing.

Riveting - A joining technique where rivets is penetrated trough two surfaces to join the metal pieces together.

Rolling - Wrought semi-manufacturing technique for aluminum products.

Secondary aluminum - Scrap that is recovered from end-of-life products.

Self-pierce riveting - A specific riveting technique, where the procedure is done in one single step.

Sink-float separation - A sorting technique that sorts scrap by differences in densities by using a specific gravity bath.

Wrought alloys - Alloys that require higher level of purity than cast alloys. Wrought alloys products are produced trough rolling, extrusion or forging.

Abbreviations

ASF - Audi space frame

BiW - Body in white

BOL - Beginning of life

CED - Cumulative energy demand

CFC - Clorfluorcarbon

EAA - European Aluminum Association

ELVs - End of life vehicles

EOL - End of life

GMA - Gas metal arc

GWP - Global warming potential

ILCD - International reference Life Cycle Data System

IPCC - International Panel of Climate Change

LCA - Life cycle assessment

LCI - Life cycle inventory

LIBS - Laser-induced Breakdown Spectroscopy

MIG - Metal-inert gas

MOL - Middle of life

ODP - Ozone depletion potential

1 Introduction

The production of primary aluminum is a very energy-demanding process, whereas recycling of aluminum is beneficial both in terms of energy savings and economy. However, it is important to point out that today most of the recycled aluminum products are down-cycled. This means that the scrap is used to make aluminum products with less requirements regarding alloy composition and impurities.

Due to the increased use of aluminum in products, the amount of available aluminum scrap is growing. This makes it interesting to investigate the possibilities for the use of recycled aluminum in products with higher purity requirements, as a step on the way to increase the overall recycling rate of aluminum. Specific requirements for product performance leads to specific requirements for the chemical composition of the scrap. This calls for better scrap sorting and sometimes also refining steps to remove impurities. Knowledge of scrap composition, and the impurity tolerance in aluminum alloys are great challenges that need to be broadened in order to achieve this goal.

The automotive industry shows an increasing interest in using aluminum in vehicle production. Today the most common way to produce Body-in-White (BiW), which makes out a significant share of the materials used in the vehicle, is from steel. Aluminum BiWs exist, but are not produced for extensive commercial use. Previous studies have compared environmental impacts of using primary aluminum instead of steel for producing BiW[2, 3, 4]. This study aims to investigate the impacts of using aluminum scrap for BiW production.

Aluminum based BiW consists of several aluminum alloys, especially from the 5000 and 6000 series, which need to be separated before reuse. This can be done by different techniques, but in the present project focus will be on laser spectroscopy. This technique is presently not in use for sorting of aluminum scrap, but an investigation on the environmental aspects and economical consequences of this process is relevant for future investments.

The primary objective of the present project is to compare three different production routes for BiW, from primary aluminum, from old BiWs and from end-of-life vehicles (ELVs). This is done by performing an Life Cycle Assessment (LCA). In order to do this, the different production routes must be described. Input/output data for the processes involved in the production routes is collected. Last, the challenges and benefits of switching from primary to secondary aluminum is enlightened.

2 Background

2.1 Aluminum Production

Aluminum is a widely used metal, but the industrial scale production is barely a century old[5]. It is a popular material for use in the construction and transport sector due to light weight. The large gap between energy consumption for primary and secondary production makes it a very suitable metal for recycling. In Figure 1, the main steps in the life cycle of aluminum products are presented. It starts with extraction from primary ore as bauxite and goes to primary production. The production of aluminum is followed by fabrication and manufacturing steps. When aluminum products are made, they go into the consumer stage. The product in question might be a beverage can, a car part or a construction material. At its end of life, the product either goes to waste disposal or is recycled back into the loop.

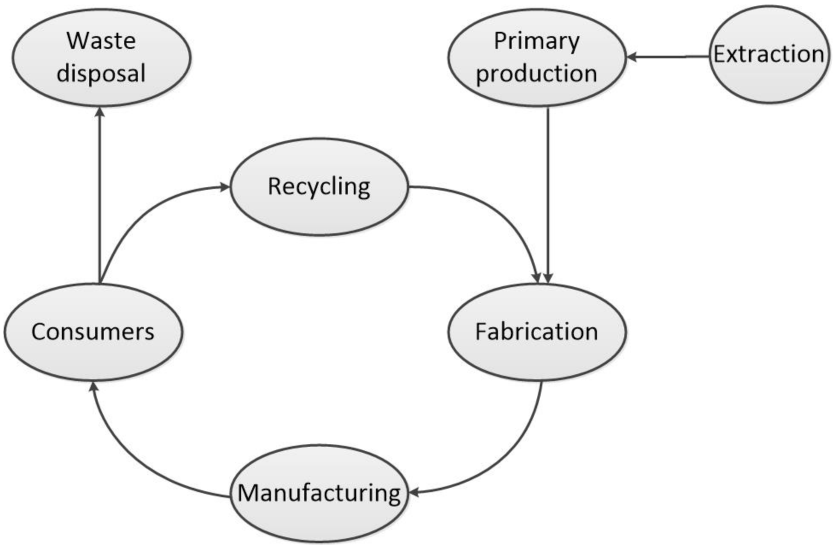

Figure 1: The main parts in the life cycle of aluminum products.

2.2 Primary Aluminum Production

Motivation for improving the recycling rate of aluminum is largely connected to the energy-demanding production from ore (primary production). It should be mentioned that reducing aluminum production from ore may potentially save large amounts of greenhouse gas emissions. The amount of

GHG emissions saved is however highly dependent on the type of energy used for the electrolysis step in the primary production of aluminum.

Primary production of aluminum can be divided into two main steps, *i.e.* the Bayer process and the Hall-Hèroult process as seen from figure 2. The first step is the Bayer process where alumina (Al_2O_3) is produced from bauxite. The second step is where alumina is electrochemically reduced through the Hall-Héroult process.

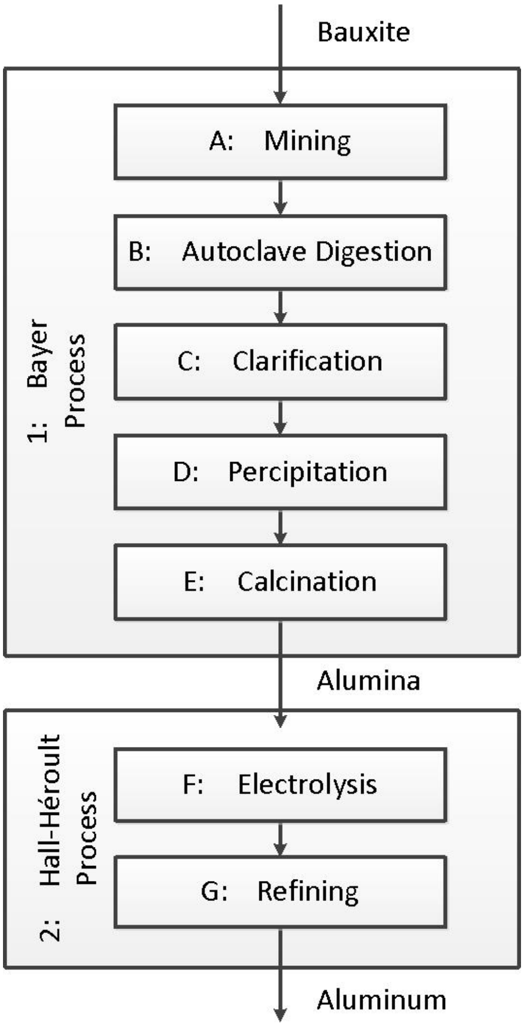

Figure 2: The main steps (A-G) in primary production of aluminum[6].

Bauxite is extracted from primary ore, and alumina is dissoluted from bauxite in a sodium hydroxide solution (step B in figure 2). This step is performed in autoclaves at temperatures between 145-250°C depending on the chemical composition of the ore[6]. Bauxite is separated from the liquor in several solid-liquid separation steps, then coarse sand fraction is separated using thickeners. The overflow is later filtered (step C in figure 2).

Step C in figure 2, is followed by the precipitation (step D in figure 2) where the liquid is cooled to supersaturate the solution. Gibbsite seed particles are added to promote crystallization of aluminum hydroxide ($Al(OH)_3$). The process conditions are carefully controlled in order to obtain the requested size and shape of the crystals. After the precipitation step slurry is separated into two fractions, *i.e.* a fine and a coarse fraction. The coarse fraction goes to calcination (step E in figure 2), where the hydroxide is decomposed and alumina powder is produced.

During the Hall-Héroult process alumina is dissolved in a molten cryolite (Na_3AlF_6) bath (step F in figure 2). The aluminum metal is dissolved on the carbon cathode, and oxygen reacts with the carbon anode. This process is operated at temperatures around 960 °C. The production is usually finished with a refining step, which may be influenced by purity requirements (step G in figure 2).

The produced metal has a purity of 99.6-99.9 wt% of Al. Molten aluminum is however, usually refined to remove small quantities of impurities.

2.3 Secondary Aluminum Production

In the book "Aluminum Recycling", Schlesinger[5] describes several factors that affect the successful aluminum recycling. First is the need for a plentiful and recurring supply of metal. The scrap needs to be concentrated enough to justify the cost of collecting it. This is often a challenge, because scrap tends to spread out rather than be concentrated in a specific region. Second there is a need for infrastructure for collection and processing of scrap. Third, recycling of used goods needs to be economically competitive with production of new products/goods.

Governments may affect the recycling rates by introducing incentives. In EU there are at present regulations on construction debris, and as a result of that the recycling rate for construction debris is relatively high. By promoting recycling with regulations and laws, the government might make recycling economically competitive with primary production.

It is a well known fact that large bulky items are more attractive for recycling than thin and more complex items. The aluminum content in items is also clearly an important factor when it comes to recycling. This is why the recycling rates for aluminum cans are relatively high, despite the fact that more processing is required[5]. Last, there must be a market for the recycled metal. Since there is a clear difference between recycled (secondary) aluminum and primary aluminum, in chemical composition and impurity levels, the potential areas for use of recycled metal should be mapped.

As there is no benefit in recycling aluminum scrap by the Hall-Héroult process, secondary aluminum is produced independently of primary aluminum, in special remelting facilities. These facilities are often located near automotive manufacturing areas[7].

2.3.1 Recycling of End-of-Life Vehicles

The recycling of end of life vehicles (ELVs), as described in figure 3, starts with collection of ELVs (Step A in figure 3). Then the fluids are distracted from the car (Step B in figure 3), and the car is dismantled in a scrapyard. Large components (Step C in figure 3), such as tires, batteries, heat exchangers and catalysts are removed. Later it is chopped and shredded into manageable pieces (Step D in figure 3).

Electro-magnetic separation distinguish between ferrous and nonferrous scrap (Step E in figure 3). This is typically done by sending the scrap down a conveyor belt equipped with magnets. This is a widely used technique in the aluminum industry. Aluminum is a non-ferrous metal, iron is ferrous so this technology separates iron from aluminum. However, the sorted aluminum scrap may still contain small amounts of iron.

Sink-float separation is a separation technique used for separation of nonferrous metal by their different densities. The shredded pieces are added to a bath with specific gravity. A common procedure is to start with a water bath (specific gravity of 1) to remove non-metallic pieces (plastics, foam, wood etc.). Then a bath with specific gravity of 2.5 separates out magnesium and higher density plastics (Step F in figure 3). The last bath has a specific gravity of 3.5 and separates out cast and wrought aluminum, leaving heavier metal pieces such as copper, zinc, lead etc.[9] (Step G in figure 3). One of the challenges with this technique is that some hollow or boat shaped metal components may be lost. It is also costly to maintain the constant density slurries.

Eddy current separation uses the large range of conductivities of different metals to sort metal scrap (Step H in figure 3). A rotor produces an ex-

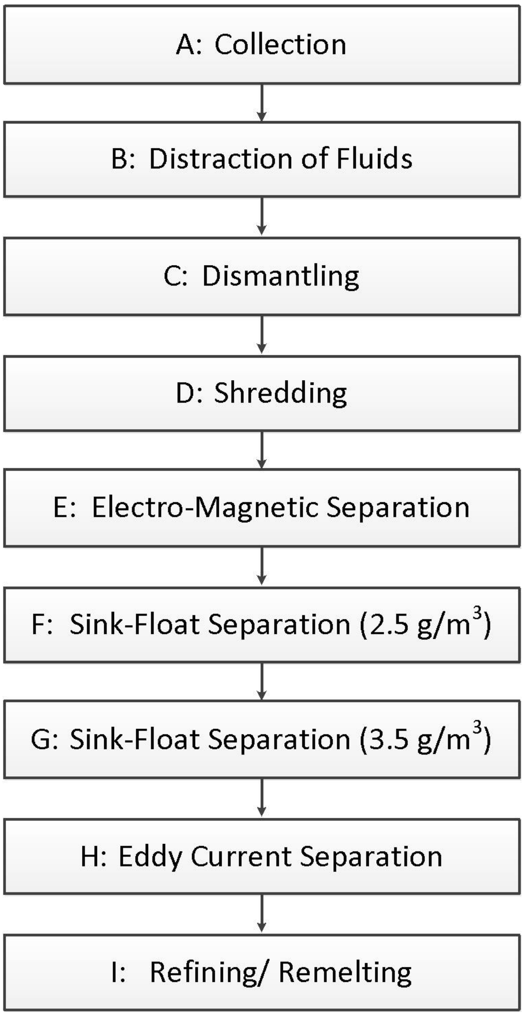

Figure 3: The most common treatment steps (A-I) for end of life vehicles[8]

ternal magnetic field which repels electrically conductive metals which are removed leaving the non-metallic particles behind. By controlling the speed of the rotor, the magnetic field is controlled. Since metals with different conductivity will produce varying eddy currents they will be thrown different distances. This allows for specific separation of aluminum pieces. However, eddy current separation does not distinguish between different alloy types and/or cast and wrought alloys. Laser sorting is pointed out as the solution to this problem[10, 11]. Today, all shredded aluminum pieces goes to secondary smelters and is transformed in to castings trough remelting and/or refining (Step I in figure 3).

2.3.2 Laser-induced Breakdown Spectroscopy

In order to achieve wrought to wrought recycling in the future, the important step is to successfully separate cast and wrought alloys. And even more specific, to be able to sort aluminum scrap by alloy type.

LIBS uses laser and optical emission spectroscopy to sort cast and wrought aluminum[9]. Figure 4 shows the basic setup of a LIBS system for sorting aluminum scrap. A conveyor belt transports the scrap. The scrap is scanned by a 3D laser line section sensor to detect the position and shape of the pieces. The LIBS module involves an xy-scanner that scans the sample. Based on the information obtained the sample is delivered to the correct bin by automatic ejection by pressurized valves.

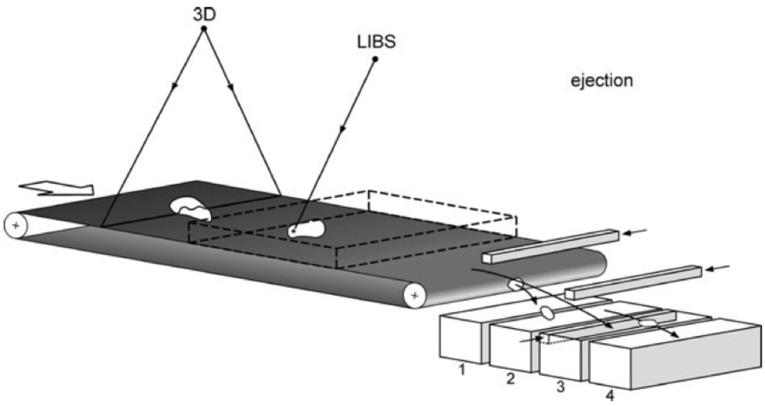

Figure 4: A Schematic view of a laser beam sorting system for sorting aluminum scrap[12].

The great advantage with LIBS is that it can sort wrought alloys by alloy family. It can also operate at high speed and with high scrap volumes. However, the laser can only penetrate a small distance into the surface of the metal so the scrap needs to be clear of all lubricants, paints and other coating. Because of the nature of aluminum, *i.e.* its reactivity, this is also problematic if an oxide layer is formed on the metals surface. This leads to the need for a decoating or cleaning step for scrap that has paint or coating.

2.4 Manufacturing

2.4.1 Semi-manufacturing Techniques

There are a great number of manufacturing techniques available for metals. The choice between them is made on the basis of properties of the metal, the desired shape and size of the finished product and cost. Semi-fabricated aluminum products may be separated into two groups, namely wrought products and cast products. The distinction between these two relates to the production methods. Cast products are produced from liquid aluminum by pouring it into a hollow cavity with the desired shape, where it is solidified. This is done in designated casting or foundry facilities. Due to the production method, casting alloys generally has a higher tolerance for impurity elements than wrought alloys. This has over the years lead to a situation where discarded wrought aluminum products are recycled back to new cast products, *i.e.* downcycling.

Typical wrought production starts with aluminum bars, ingots or billets, which are either rolled or extruded into the desired shape. There are several techniques available for rolling and extrusion. This text describes the techniques relevant for the production of the aluminum body used in Audi A2.

Casting
There are multiple casting techniques available, and as previously stated the requirements for casting alloys are less stringent than for wrought alloys.

However, during the last years, developments in casting techniques has introduced possibilities for higher requirements for cast alloys as well. This is partly due to the increasing demand for lightweight solutions in automotive industry. An example of such a casting technique is High-Q-Cast®, which is a specific vacuum-assisted high pressure die-casting technique. It is used for high quality demanding products as is the case for structural car components, such as the ones used in the Audi space frame.

Hydroforming
Hydroforming is an extrusion manufacturing process used for ductile metals where fluid pressure is used to achieve desired shape[13]. There are two types of hydroforming; sheet metal hydroforming and tube hydroforming. The latter is the most relevant technique for the extruded sections of the Audi space frame. The tube hydroforming technology is attractive for automotive applications due to its low cost, low weight, possibilities for improved quality and high-volume production[13].

Hydroforming is a technique that has several advantages over other manufacturing techniques. Hydroforming often involves lower tooling cost and fewer process steps. It may also reduce the total number of parts and lead to total mass reduction[14].

Rolling
There are two types of products made from rolling; plates and sheets. Plates have a thickness greater than 6 mm, and are used for structural applications such as ship hulls, boilers, bridges and more[15]. Sheets are generally thinner than 6 mm, and used for automobile bodies, food and beverage containers, kitchen appliances and office equipment.

Sheet rolling is a wrought technique where the sheet ingots are pressed into sheets in a rolling mill. The sheet ingot is first homogenized (heated to 500-600°C)[16], then the sheets are rolled back and forth in the breakdown mill until the desired thickness is obtained. To increase strength, the sheets may be cold rolled or heat-treated. Lastly, the sheet is trimmed to its final size, or machined further to form more complex shapes.

2.4.2 Product Manufacturing

There are many ways to produce aluminum products from semi-fabricated products such as sheets, extruded sections etc.

Welding is a metal processing technique where two metal pieces are joined together, either through fusion welding, brazing and soldering or solid state welding[15]. Fusion welding is when the metal pieces are melted together trough heat. Solid state welding is when the metal pieces are joined together without heat. The latter technique requires clean surfaces and sufficient pressure for the metal surfaces to form bonds and produce a strong joint. Brazing and soldering allows for low temperature bonding. Filler metals are placed in or supplied to the joint. The contact point is heated trough an external heat source and a strong joint is formed. Soldering temperatures are lower than for brazing[15].

Laser Welding

In laser welding, a laser beam heats up metals and join them together. There are numerous types of lasers that may be used for laser welding. The laser beam can be focused on a very small area and has high energy density. This means that the penetrating capability with laser welding is good, and this technique is therefore suitable for deep and narrow joints[15]. The laser beam may be emitted in pulses or as a continuous beam. The former is used for thin materials, the latter for thick sections and deep welds. Laser welding can easily be automated, no vacuum is required and the quality of the weld is good. The disadvantages are safety considerations and equipment costs.

Metal-inert Gas Welding

Metal-inert gas (MIG) welding is a type of gas metal arc (GMA) welding. In arc welding, the heat required is obtained from electrical energy. A consumable or non-consumable electrode is used. In GMA welding the weld area is shielded by an external source (argon, helium, carbon dioxide or other gaseous mixes), keeping contaminants away from the weldment[15], while a bar wire is fed trough a nozzle. MIG welding is a widely used, relatively simple technique suitable for many purposes. It is also rapid, easily automated and economical.

Self-Pierce Riveting

Riveting is the most common joining technique of permanent or semipermanent mechanical joining. In traditional riveting, the rivets are placed in a hole and deformed at the end. Riveting may be done in room temperature or at higher temperatures[15].

Self-pierce riveting is a rivet joining technique where, in a single step, a punch drives a rivet which pierces the sheet. A shaped die on the underside responds to the applied force and causes the rivet tail to flare within the bottom sheet[17].

2.5 Body-in-White

2.5.1 Traditional Body-in-White

Body-in-white (BiW) is the structural part of the car before any separate components like motor, glass, seats and electrical components, are added. It represents a large share of a car's total mass, and therefore also contributes to a significant share of the vehicles fuel consumption. The requirements for a car body/BiW may be summarized as follows:

- Strength
- Ductility
- Drawabillity index
- Surface finish

BiW has traditionally been made of steel. This is mainly due to good formability, large supply, strength and low cost of steel. In addition, steel with zinc coatings provides corrosion resistance.

However there are some disadvantages for steel including heavy weight and sensitivity to corrosion, if its not coated. Corrosion challenges has been resolved by a range of zinc coated steels, and higher strength steel has been produced which enabled reduction in thickness and improved performance.

2.5.2 Aluminum Body-in-White

The main feature of aluminum that makes it interesting for car body application is the low density compared to steel. It also posses the great advantages of recyclability like steel. The aluminum alloys used in car body parts are also corrosion resistant.

The main disadvantage of aluminum car body parts are high production cost compared to steel. It also has poorer formability and is less readily welded than steel[18]. Due to the fact that the main way to produce BiW today is from steel, a shift towards aluminum would also require implementation of new production techniques and equipment.

The strength of aluminum sheet panels and extrusions are approximately the same as steel body panels, but the rigidity is lower than steel[10]. This is partly due to the difference in modulus of elasticity that is about a one-third for aluminum compared to steel. This may be compensated through increased wall thickness. Table 1 compares some properties of aluminum and steel.

Table 1: Properties of steel and aluminum[10].

	Steel	Aluminum
Module of elasticity (N/mm^2)	190.000 - 220.000	60.000 - 80.000
Strength (N/mm^2)	290 - 470	260 - 350
Density (kg/dm^3)	7.85	2.7

Several cars with aluminum BiW has been produced over the years, however most are luxury cars, which are not produced in large scale. Hirsch investigated the use of aluminum alloys in light-weight car design [19]. Several cars with aluminum BiW was studied. Table 2 shows the production volumes and BiW weight of the cars studied by Hirsh. It is stated in the paper that aluminum solutions are well-established in several car components, but preferentially in high class cars. It is also pointed out that since the BiW contributes to a high share of the cars total mass (up to 30%), it is trough minimizing the weight of this component, that the highest weight savings can be reached.

Table 2: Cars containing aluminum BiW[19]. *Excl. panels and outer skin **Scheduled

Car	BiW weight (kg)	Prod. volume (cars/year)
Aston Martin Vanquish	145*	350
BMW Z8 Roadster	300	2.500
Audi A8 (D3)	277	25.000**
Audi R8	212	
Jaguar XJ Model y 2002	295	30.000

Fridlyander *et al.* performed a literature study concerning the efficiency of aluminum alloys in structural automotive parts[20]. The investigation lead to information on suitable aluminum alloys, based on the performance requirements. High strength, high corrosion resistance, good formability, dispersion hardening and limited grain size are requirements that must be fulfilled. The study concludes that two types of aluminum alloys are used for body parts, *i.e.* the nonheat-treatable alloys from the 3000 and 5000 series, and the heat-treatable alloys from the 2000 and 6000 groups. The most popular non heat-treatable alloys are represented by the 5182-0 sheets. From the 2000 groups the alloys 2008 and 2036 is most widely used. In

Europe the most common alloy for external paneling is 6012, and in North-America 6111 and 6061[20].

Miller *et al.* discuss the recent development in aluminum alloys for use in the automotive industry[21]. Cars containing aluminum body parts like Audi A8, and the updated Audi AL2, Ford AIV, Honda NSX are studied and it is stated that the search for suitable alloys for body components is narrowed down to a relatively small number of alloys. As Fridlyander, the emphasis is laid on the need for good formability, strength and high surface quality. Table 3 shows the alloys commonly chosen for Europe and North America.

Table 3: Aluminum Alloy Choice[21]

	Europe	North America (%)
Outer panels	6016-T4	6111-T4
Inner panels	5051/5182/6181A	6111/2008/5182
Structure/sheet	6xxx-T4	5754-O
Structure/extrusion	6xxx	6xxx

Audi Space Frame

In 1999 Audi A2 (see figure 5) was launched with a modified Audi space frame(ASF)[17]. Audi A2 was suitable for larger production volumes than the previous models. The design allowed for BiW production rates at up to 300 vehicles per day[22]. The amount of component parts where reduced in order to minimize costs, and make it suitable for mass production.

Figure 5: Audi A2[1]

The weight of aluminum body in Audi A2 is 153 kg, and the total weight of the car is 825 kg. The average fuel consumption was 2.99 l per 100 km[17]. The ASF consists of extrusions, castings and sheets (see figure 6).

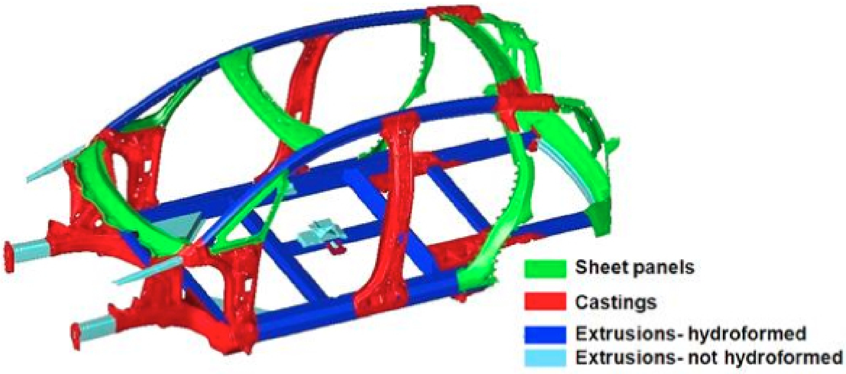

Figure 6: Audi Space Frame[17]

2.6 Previous Work

There are several studies conducted on application of aluminum in automotive structural parts that addresses the challenges that must be overcome. Some comparisons of aluminum body and the traditional steel body are also found. There are however, few studies comparing the use of secondary aluminum with the use of primary for producing BiWs.

Sujit Das conducted life cycle comparisons of energy usage and CO_2 emissions for aluminum vs. conventional and ultralight steel auto bodies[2]. The results concluded that the benefits of aluminum are significantly less comparing to ultralight steel autobodies. The increased energy use for manufacturing of aluminum bodies (BOL), removes the benefits of less energy consumption during the time of use (MOL). This leaves the energy savings in the recycling stage as the main contributor to the total life cycle savings of aluminum. Das states that recycling contributes to 29% and 73% of the total energy savings from steel and ultra light steel, respectively.

Time is seldom accounted for when classic LCI studies are performed. This limits the ability to account for the dynamics in a system, *i.e.* the availability of aluminum scrap suitable for BiW production.

Peter Stasinopoulos *et al.* uses a system dynamics approach in order to account for changes in the resource flow and environmental impact over time[23]. They compared the life cycle energy consumption of car BiWs made from steel and aluminum. Two dynamic processes are incorporated, *i.e.* the flow of BiWs in and out of the car fleet and the recycling of aluminum from EOL BiWs back into new BiW production.

The model gives results for both one single product (one BiW) and the whole car fleet. Results for one product shows that aluminum BiW consumes less energy than a steel BiW over a single life cycle. However, the results for the entire car fleet implies that the energy benefits of using aluminum BiWs will show first after an extended period of time. Due to the long lifetime of BiWs there will be a slow decay in the flow of steel BiWs out of the fleet. Similar, the recycling of old aluminum BiWs into new aluminum BiWs will start at zero and grow as the BiW reach end of life. The study concluded that a product-based LCI overestimates the short term energy benefits of aluminum BiWs. This is true as it does not account for the stock of preexisting steel BiWs, and the time needed for them to decay out of the car fleet. Seemingly, the long term effects on energy consumption is underestimated, as it does not account for changes in the availability of recycled aluminum.

3 Theory

3.1 LCA

The increasing focus on the environmental aspects of products and services has lead to the development of methodologies for addressing those issues. Life Cycle Assessment (LCA) is such a methodology. The goal of LCA is to identify possibilities for reducing the environmental impacts of systems[24] and the whole life cycle is considered. LCA is divided into four interacting parts, as seen in figure 7.

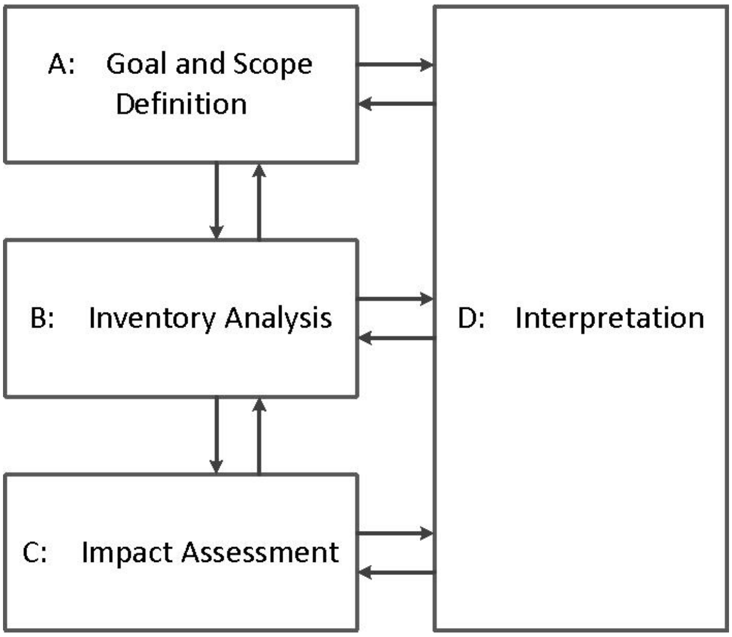

Figure 7: The framework of an LCA

3.1.1 Goal and Scope

At first the goal and scope are defined, see stage A in figure 7. This is where the purpose of the study is defined, together with system boundaries, assumptions made and data requirements for completing the study. The specific purpose of the study must be clarified in order to choose the best methodologies. The purposes of an LCA may be many, like possible improvements in a products life cycle, identifying environmental problems or comparing environmental performance of products.

A functional unit is also chosen in the goal and scope step, typically 1 unit of a product or 1 kg material. This functional unit serves as a basis for comparison to other competing products. The functional unit is overall defined as a quantified performance of a product system for use as a reference unit[25].

The functional unit also contains a time horizon. A time horizon may be the duration of use (in time) or the extent of time the function is actually provided [26]. For a car this would be the average lifetime of the car, *e.g.* 12 years, or the amount of km driven, respectively. When comparing car models the latter is more suitable. The specific information for this project will be given in the section called system description.

The scope of the study involves deciding on options to model, impact categories to include, impact assessment method and definition of system boundaries.

An important aspect that must be considered is allocation. Allocation is best understood by an example. If data for an entire production site is gathered, inputs and outputs must be allocated in order to obtain data for the process of interest. This means that allocation is used to split up the environmental loads when several products share the same processes.

3.1.2 Inventory Analysis

The second part is the inventory analysis (see stage B in figure 7), where data for the relevant inputs and outputs are gathered and quantified for all processes in each of the life cycle stages[24]. Inputs can be any product, material or energy flow that enters a process. Outputs can be any product, material, waste, emissions or energy flow that leaves a process[25].

There are several aspects of the data collection that should be addressed due to their potential effect on the results. The quality of the data is the most important. Questions like, is the data from a reliable source and when was it collected are important. The geographical origin of the data is another aspect that should be taken into consideration. Sometimes there may also be several technologies available for a process, and the researcher needs to investigate and choose the most relevant for the study.

Data for the inventory may be collected from several sources, such as companies, producers, databases, environmental reports, company and public statistics. In some cases the goal of an LCA can be fulfilled by performing only an inventory analysis and interpretation, which is called an LCI study[25]. The inventory data used for this project is presented in the inventory section.

3.1.3 Impact Assessment

The third part is the impact assessment (see stage C in figure 7). An impact assessment may consist of 4 steps (classification, characterization, normalization and weighting) which is addressed in the following text.

Classification
In this step, environmental burdens, that were identified during the inventory stage, are grouped into effects on local and global environments. This is done by grouping the environmental burdens into impact categories. Each environmental burden may contribute to one or several impact categories. For instance, clorfluorcarbon (CFC) is an environmental stressor that contributes to the impact category Global Warming Potential (GWP) and Ozone Depletion Potential (ODP).

Characterization
The impact categories may receive contributions from several environmental stressors. An equivalence factor indicates how much a substance contributes to an environmental impact, compared to a reference substance. This is called characterization. The GWP of a substance is measured relative to the impact of 1 kg CO_2. Methane has an equivalence factor of 25, giving 1 kg of methane an GWP of 25 kg CO_2-equivalents.

Normalization
Normalization is when impact scores is compared to a reference score. This is done by dividing the impact results by a reference value. A typical reference value may be the highest value, or the total emissions for a given area on a per capita basis. Choice of a suitable reference value is highly connected to the goal and scope of the LCA.

Weighting
Weighting is emphasizing the most important potential impacts[27]. This is done by assigning relative values to different impact categories based on their importance. As an example, human toxicity may be of more importance in a highly populated area, than uninhabited areas. One major challenge with weighting of impact results is the subjectivity in assigning weight to different categories.

Communicating the results of an LCA/LCI study may be challenging. Two types of assessments exist to overcome this challenge; midpoint and endpoint assessment. If the impacts assessment stop after classification and characterization it is called an midpoint assessment. An endpoint assessment includes normalization and weighting. A midpoint assessment is problem-oriented, as is reflected in the category names; climate change, human toxicity etc. Whereas an endpoint assessment is damage-oriented (human health, natural environment etc). The benefits of an endpoint assessment is that it is more readily communicated, but the drawbacks is more uncertainty introduced by normalization and weighting.

Over the years, many impact assessment methods for performing an LCA has been developed. In a handbook for the International Reference Life Cycle Data System (ILCD) published by the European Commission Joint Research Centre (JRC), an analysis of existing impact assessment methodologies was performed[28]. This text addresses only some of them, in order to give the reader an insight in the methodologies available, seen below.

- Eco-indicator 99: An endpoint method that don't separate midpoints. Weighting is included. Three different perspectives is separated out; hierarchist, individual and egalitarian. Each with a consistent set of value choices[28].
- CML 2002: Aims to provide the best practice for midpoint indicators using the ISO14040 series of standard. CML 2002 includes recommended methods for normalization, but no recommended methods for weighting[28].
- ReCiPe: Integrates the midpoint and endpoint approach from CML 2002 and Eco-indicator 99.

The results from the impact assessment in this project will be presented in the section called results.

3.1.4 Interpretation

The forth part is the interpretation step (see stage D in figure 7). This is where the results of the inventory analysis and/or impact assessment are discussed[25].

The interpretation should consist of conclusions, limitations of the study and recommendations for improvement. The results should also be analyzed by performing uncertainty checks, as well as a sensitivity analysis. A sensitivity analysis is done to examine whether some specific data elements influence the results more than others. It is a systematic procedure for examining the effects of choices made for data and methods in the study.

A contribution analysis may also be performed. This involves comparing contributions from the life cycle stages or groups of processes to the total results[27].

It is essential that the interpretation stage of an LCA shows good transparency regarding the limitations and the weakness of the results. This is an important step in preventing misuse and misunderstandings of the study.

The interpretation stage of this project will be presented in the section called discussion.

3.2 Recycling in LCA

There is a large gap between the energy consumption for primary production and the energy consumption for secondary production of aluminum. This means that accounting for recycling is crucial when LCA on aluminum products is performed[29]. This might be done in two ways. The first way is to account for the amount of used material that is recycled after end-of-life, the second way (the cut-off approach) is to account for the recycled material used in a product.

The first way is argued to be the best for materials with a growing demand [29]. This is the case for aluminum. If you make a product from recycled material and this product is not recycled after use, primary metal will have to replace the material which is not recycled. So by recycling, credit is given for avoided production of primary aluminum. There are some drawbacks with this method, for instance the manufacturer will not be credited for using recycled material. Another limitation is the fact that part of the aluminum recycled may replace recycled aluminum in the production, not primary aluminum.

By applying the cut-off approach, the fate of the product after use is not considered; *i.e.* whether it, or it's material content is recycled. Even if all aluminum products where recycled after use, this would still not be enough to cover the growing demand for aluminum. The second method gives the manufacturer credit for using recycled aluminum. If the goal of an LCA is to investigate the potential environmental savings of using secondary aluminum in a product the cut-off approach (second method) is best suited.

4 System Definition

This project investigates the life cycle of an aluminum BiW, made with three different types of inputs to the production, *i.e.* three scenarios. The end of life (EOL) and middle of life (MOL) for the BiW are the same for all three scenarios. The difference between the scenarios are in the production of the BiW (BOL). The three types of inputs that is considered are primary aluminum, sorted scrap aluminum from old BiWs (closed-loop recycling) and sorted scrap aluminum from ELVs (open-loop recycling), respectively.

The input for the production of BiW from primary aluminum (scenario 1) includes several steps. First the raw material extraction from bauxite, then production of alumina by the Bayer process and last, production of aluminum by electrolysis (Hall-Héroult process), as seen in figure 2 in the background section.

The input for the production of BiW from scrap aluminum from old BiWs (scenario 2) includes collection and transport of old BiWs as well as shredding and sorting by LIBS.

The input for the production of BiW from scrap aluminum from ELVs (scenario 3) includes several steps. First the collection and transport of ELV scrap. Then the sorting steps as shown in figure 3, and last the sorting by LIBS.

The motivation for making these three scenarios and comparing them is to show the potential environmental benefits from switching from primary to secondary aluminum for the production of BiW.

4.1 Goal

As already stated, the goal of the current LCA to investigate the potential benefits of recycling aluminum in a high-end product such as BiW. A full-scale LCA is performed, addressing several other impact categories in addition to energy consumption and GWP, potential trade-offs will also be demonstrated. The main aim of the present study is to provide a better insight on how investing in scrap treatment technologies can be beneficial compared to continued primary production in the future.

4.2 Scope

This study compares primary production of aluminum for BiW to secondary production of aluminum from old BiWs and ELVs. Comparisons with steel BiWs and other lightweight solutions are done in several other studies[2, 3, 4] and will not be addressed here. This study focuses on comparing primary production with secondary production, and hopefully enlightens the challenges and benefits with these three scenarios.

The study is based on information obtained from the Audi Space Frame (ASF) car body used in Audi A2. The car is chosen because of the availability of information, as well as the suitability for mass production. As mentioned previously, most of the luxury cars produced with aluminum BiW are not suitable for mass production. The ASF was originally made for Audi A8, and used in several other cars. Before using the ASF in Audi A2, some changes where made. The specific data for the body of Audi A2 is shown in table 4. Audi A2 weight 825 kg in total, and the BiW 153 kg. From the table it is seen that outer and inner sheet panels is the largest parts of the BiW with 60% of the total weight, 91.8 kg. Castings contributes with 22% or 33.66 kg of the total BiW weight, and extruded parts 18% or 27.54 kg.

Table 4: Composition of Audi A2 space frame car body[17]

Part	wt%	Part	Alloy)
Sheet panels	60	Outer panels	AA6016
		Inner panels	6181-A
Castings	22		Aural-2
Extrusions	18		6014/6060

As seen in table 4 the ASF consist of 4 different alloys; AA6016, 6181-A, Aural-2 and 6014 or 6060. For this project 6014 is chosen as the alloy used for the extruded parts. Table 5 shows the max amount of alloying elements allowed in the relevant alloys for the ASF used in Audi A2. Data was found for both average, maximum and minimum alloying element content. For this specific project the maximum values where found to be the most relevant since the input is scrap for two of the scenarios. By allowing maximum content, a minimum need of refining is ensured.

Table 5: Alloy composition, wt% of grade (maximum allowed element content)[30][31].

Element	6014	6016	6181-A	Aural-2
Fe	0.35	0.5	0.45	0.2
Si	0.6	1.5	1.2	11
Mn	0.2	0.2	0.15	0.55
Cr	0.2	0.1	0.1	
V	0.2			
Ti	0.1	0.15	0.1	0.08
Cu	0.25	0.2	0.1	0.6
Mg	0.8	0.6	1	0.6
Zn	0.1	0.2	0.2	
Sr				0.016

4.2.1 Functional Unit

The functional unit is set to be one piece (1p) of aluminum containing BiW with the material and chemical composition defined in table 4 and 5. The lifetime of the BiW is set to 200 000 km driven. This is the same as the lifetime of the car. The weight of the BiW is 153 kg and the total weight of the car is 825 kg. The fuel used is petrol and the fuel consumption is 0.00388 kg per km for one BiW. This value is obtained by allocating a share of the fuel consumption to the weight of the BiW.

4.2.2 System Boundaries

This study includes the three main life cycle stages of the BiW, *i.e.* production, operation and EOL treatment. The only part of the life cycle where the processes varies for the different scenarios is the production of BiW, where the input is primary aluminum, secondary aluminum from old BiWs or from secondary aluminum from ELVs. The production steps are the same for all three inputs, but the steps from collection of scrap or raw material extraction to the alloy/ingot production differs.

The modeling is done with SimaPro (PRè Consultants 2012), and the LCI database Ecoinvent v 2.2 (Ecoinvent Centre 2010)[32]. The impact assessment mode used in this project is based on recommendations given in the International reference Life Cycle Data system[26]. This is a midpoint method that is based on a European context and has 16 midpoint categories. Cumulative energy demand is also included (CED), which has 6 impact categories.

Impact categories included:

1. Climate change: Global Warming Potential (GWP)
2. Ozone depletion: Ozone Depletion Potential (ODP)
3. Human toxicity, cancer effects
4. Human toxicity, non-cancer effects
5. Particulate matter
6. Ionizing radiation HH (Human health)
7. Ionizing radiation E (Ecosystems)
8. Photochemical ozone formation
9. Acidification
10. Terrestrial eutrophication
11. Freshwater eutrophication
12. Marine eutrophication
13. Freshwater ecotoxicity
14. Land Use
15. Water resource depletion: Freshwater scarcity
16. Mineral, fossil and renewable resource depletion

Cumulative energy demand(CED):

1. Non-renewable, fossil
2. Renewable, water
3. Renewable, wind, solar, geothermal
4. Renewable, biomass
5. Non-renewable, biomass
6. Non-renewable, nuclear

4.3 Scenario Descriptions

4.3.1 Scenario 1: Primary Aluminum

This scenario involves the production of aluminum BiW from primary produced aluminum. The life cycle, as illustrated in figure 8, starts with extraction of bauxite from ore through mining (BOL). As previously discussed the process further continues with the Bayer process and the energy-intensive Hall-Héroult process. Aluminum is then melted and alloying elements are added and/or removed in order to achieve the required alloys. Further production is done either by casting (in a foundry facility), extrusion or rolling, depending on which part of the BiW is produced. The castings, sheets and extruded profiles are combined to produce the BiW, trough several fabrication techniques, *i.e.* laser welding, MIG welding and self-pierce riveting. Self-pierce riveting and coating of the BiW are not included in this model, due to lack of applicable data. The BiW is transported to the consumer where it is used in the vehicle (MOL). After 200 000 km the BiW is assumed to be discarded and transported to EOL treatment.

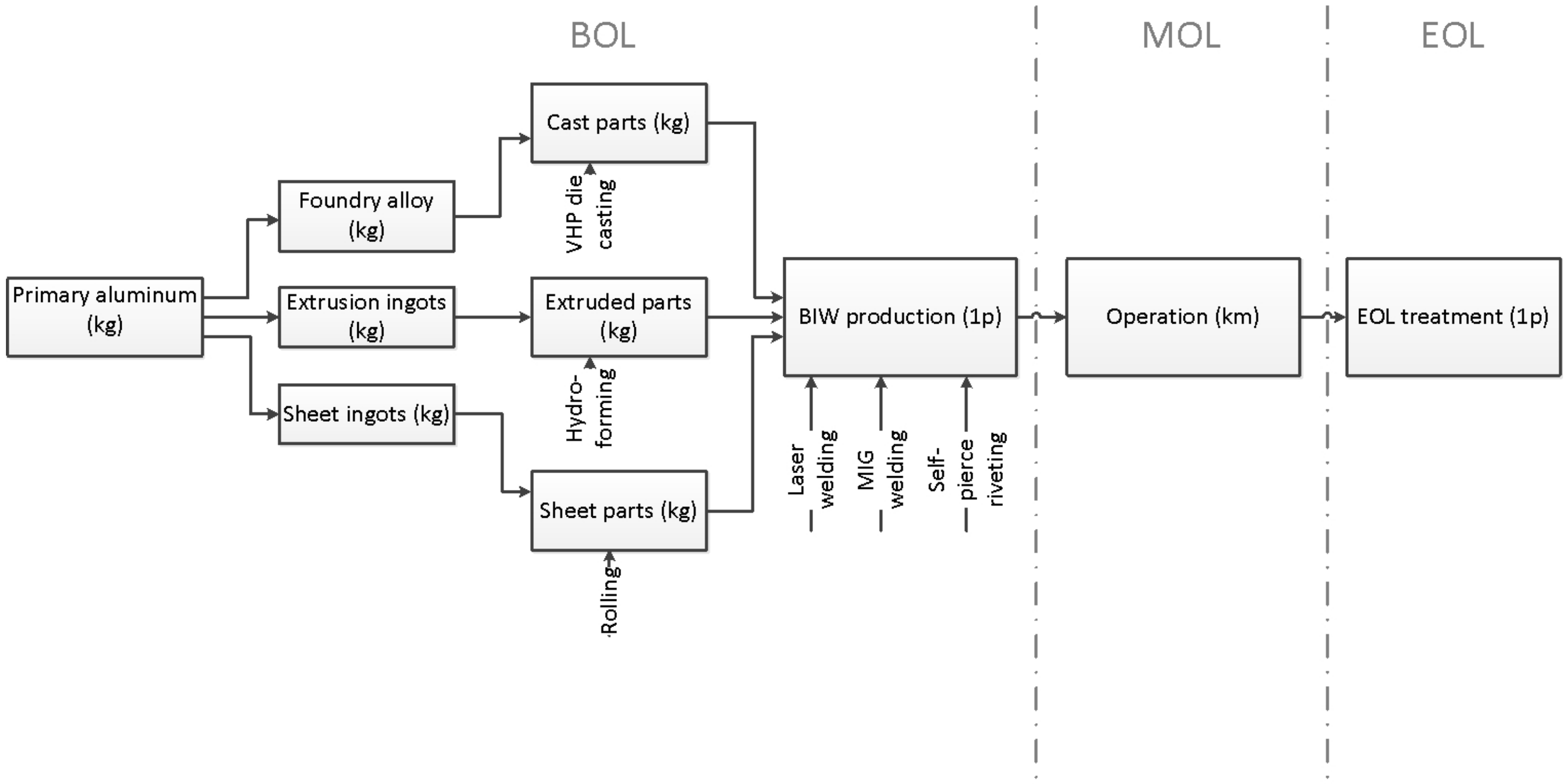

Figure 8: LCA flow sheet for scenario 1: The processes in the life cycle of an aluminum BiW made from primary aluminum.

4.3.2 Scenario 2: Closed-loop Recycling

This scenario involves the life cycle of the BiW produced by a closed-loop recycling, *i.e.* BiW to BiW recycling. The life cycle starts with the collection of ELVs (BOL), as seen in figure 9. The vehicles are disassembled and shredded and sorted through LIBS. Since the EOL BiWs are known to be made of aluminum, the normal scrap sorting techniques, like magnetic, sink-float and Eddy current sorting are unnecessary. However, the shredded pieces consists of different aluminum alloys that makes out the BiW and these pieces must be separated. Therefore LIBS is implemented as a sorting step in order to obtain required purity, *i.e.* aluminum scrap sorted by alloys. After the scrap is sorted trough LIBS, it is melted and cast, sheet and extrusion ingots are produced. These are used in the respective parts and assembled to a BiW trough the same technologies as for scenario 1. The rest of the life cycle is the same as for scenario 1; transport to user, MOL and EOL treatment.

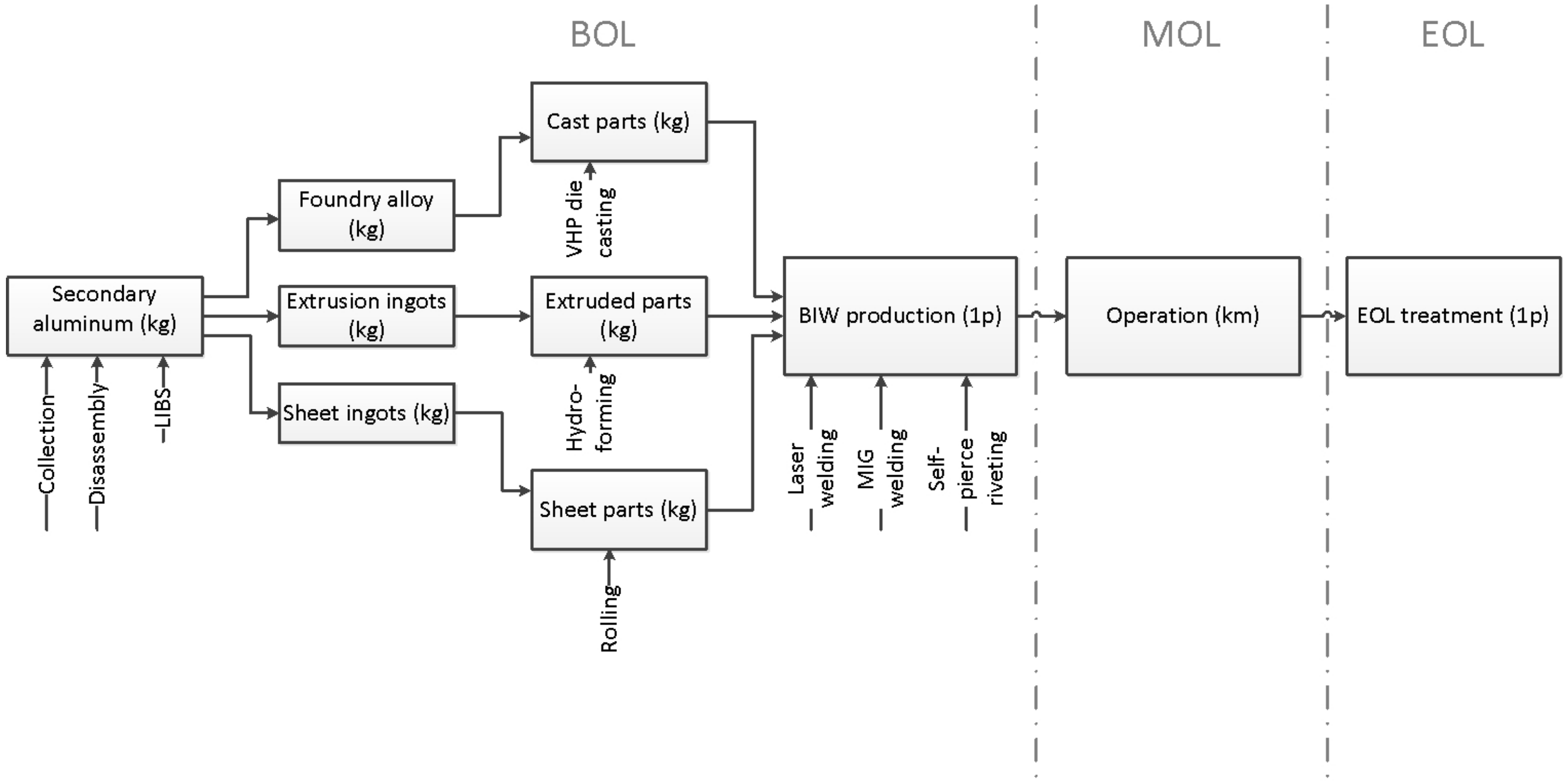

Figure 9: LCA flow sheet for scenario 2: The processes in the life cycle of an aluminum BiW made from old BiWs.

4.3.3 Scenario 3: Open-loop Recycling

Scenario 3 involves the life cycle of the BiW produced from open-loop recycled aluminum. The steps in the life cycle can be seen from figure 10. It starts with collection of raw material, which in this case is ELVs. The ELVs is recycled through common sorting techniques. This procedure starts with fluid extraction and dismantling before the vehicles are shredded into small pieces. The pieces are sorted through several sorting techniques; electromagnetic separation, sink float separation (specific gravity 2.1), sink-float separation (specific gravity 3.1) and eddy current separation. The last sorting step is sorting trough LIBS. After this step the scrap is melted and used as input for the cast, sheet and extrusion ingots. The rest of the life cycle follows the same route as for scenario 1 and 2.

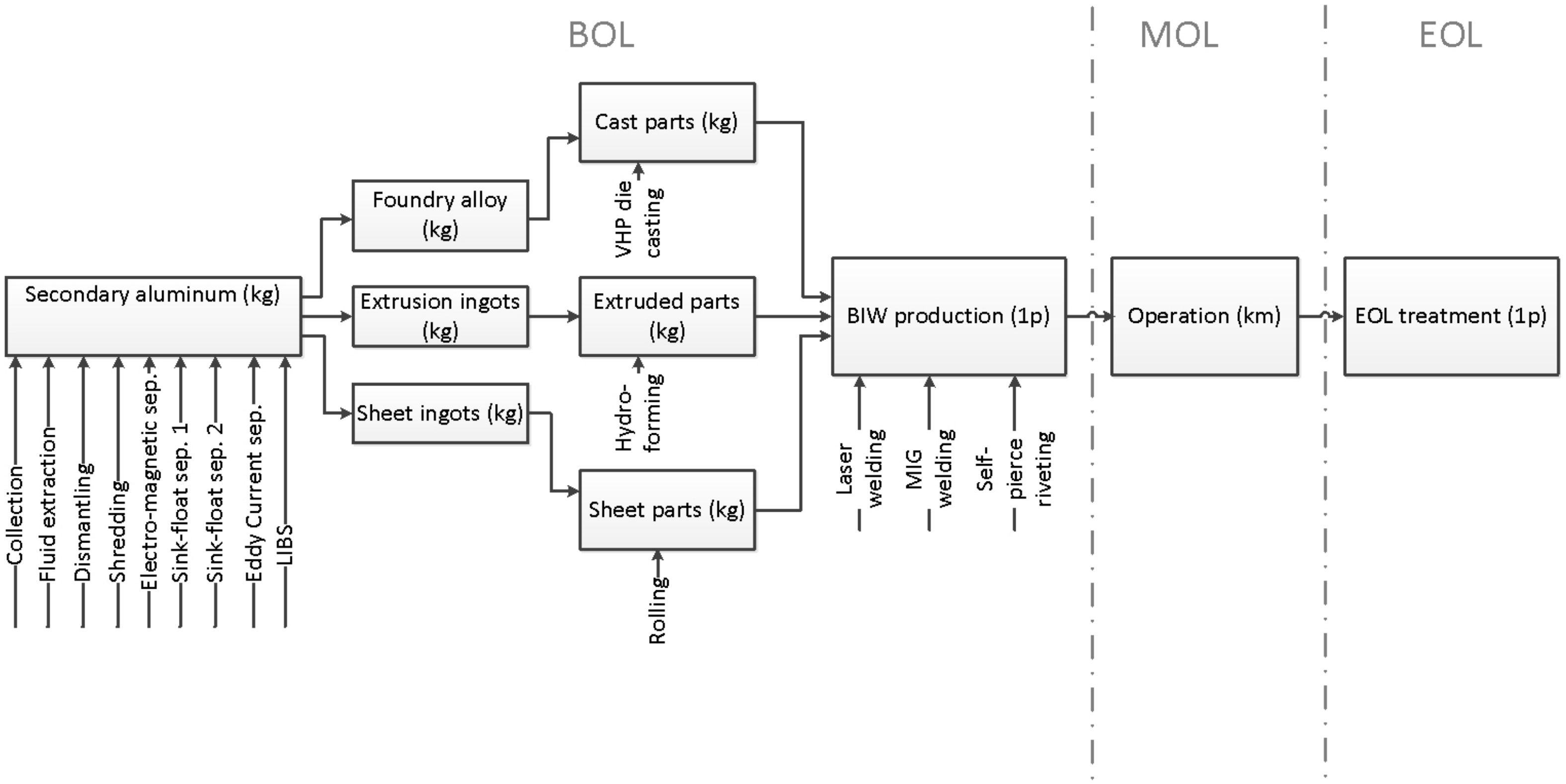

Figure 10: LCA flow sheet for scenario 3: The processes in the life cycle of an aluminum BiW made from ELV scrap.

5 Inventory

The inventory for this LCA is primarily based on existing processes in the Ecoinvent database[32], and processes made for the SupLight project *LCA/LCC Tools for Lightweight Solutions*[33]. Some processes are designed specifically for this work based on findings in literature. Whenever adequate data can not be assessed, assumptions are made. This is specifically described in the inventory description below.

Electricity mix used is *European mix, Electricity for SuPLight*[33]. It contains an electricity mix from different European countries; Switzerland 27.8%, Hungary 11.3%, Poland 50.7% and Slovakia 10.2%.

Transport is discussed in appendix A1.

Three life stages are distinguished in this project; production (BOL), operation (MOL) and end of life treatment of BiW (EOL). The operation and EOL treatment of BiW are the same for all three scenarios. These two are described first, before moving to the production of BiW. Process names are written in italic font.

5.1 Body-in-White Operation

The process *BiW operation*, designed for this project, represents the use stage of the BiW (MOL). The car is assumed to drive 200 000 km throughout its lifetime. The transport of the car to the ELVs collection site is assumed to be included in MOL. The input for this process is *Operation, passenger car, fleet average 2010/RER U*, where RER indicates that the numbers are from Europe. The output is *BiW Operation*.

The process *Operation, passenger car, fleet average 2010/ RER U* is an Ecoinvent process(see table 6), with *Petrol, low-suphur, at regional storage/ CH U* as input. RER and CH means that the process contains data from Europe and Switzerland, respectively. U means that it is an unit process, not a system process. Since the case car, Audi A2 weight is significantly less than an average car fleet, the petrol use is changed. The process *Petrol, low-suphur, at regional storage, CH U* is modified as to correspond to the given petrol use for Audi A2, 2.99 l per 100 km. This includes lowering the emissions to air related to fuel consumption.

Table 6: Inventory for the process: *BiW operation.*

Input	Amount	Unit	Source
Petrol, low-sulphur, at regional storage	0.02093	kg	Audi.com
Output			
Operation, passenger car, petrol	1	km	[32]

5.2 Body-in-White End-of-Life

The process *BiW EOL* was also designed for this project (see table 7). The outputs are *BiW EOL* and the Ecoinvent process *Recycling aluminum/RER U.* The latter process is an empty process due to the cut-off for recycling. This means that the recycling benefits and cost are allocated to the production of the recycled aluminum, and should therefore not be accounted for in the EOL stage.

Table 7: Inventory for the process: *BiW EOL.*

Output	Amount	Unit	Source
Recycling aluminum/ RER U	153	kg	[32]
BiW EOL	1	p	

5.3 Body-in-White Production

As already mentioned, the MOL and EOL processes are the same for all scenarios. That is not the case for the BOL process, *i.e.* the production of the BiW. The inventories for BOL for the three scenarios will be addressed below, starting with scenario 1.

For the process, *BiW Production Primary* the inputs and outputs is listed in table 8. The processes *Sheet panels for BiW*, *Extruded sections for BiW* and *Cast parts for BiW* are designed for this project. In addition to the three types of parts used to manufacture the BiW, there are also the process of joining the parts. Three joining techniques are used to assembly the BiW, laser welding, MIG welding and Self-pierce riveting. Unfortunantly no specific data for these joining techniques were found. Laser and MIG welding are represented by the Ecoinvent process *Welding, arc, aluminum, RER, processing, Alloc Def, U.* This process contains MIG welding with helium as a protective gas. Self-piece riveting is left out due to the lack of data. The same is done for coating of the BiW. These processes is however is the same for all three scenarios. Table 8 also shows the weight and unit of the inputs, as well as references to the literature. Manufacturing of the three different parts is further discussed below.

Table 8: Inventory for the process: *BiW production*.

Input	Amount	Unit	Source
Sheet panels for BiW	91.8	kg	[17][34]
Extruded sections for BiW	27.54	kg	[17][34]
Cast parts for BiW	33.66	kg	[17]
Welding, arc, aluminum	20	m	[17]
Welding, arc, aluminum	30	m	[17]
Transport, freight, lorry >32 metric ton	306	tkm	[32]
Output			
BiW production	1	p	

The BiW consists of three different parts; sheet, extruded and cast parts. The aluminum ingots used in production of these parts are different for the three scenarios. For scenario 1, the input is ingots from primary production, whereas for scenario 2 and 3 the input is ingots from secondary production. However, the production processes of these three parts of the BiW are similar for all three scenarios. The inventories for these production processes are described below, with primary aluminum ingot as an example.

5.3.1 Production of Sheet Panels for Body-in-White

One of the three types of parts used for the BiW is inner and outer sheet panels. They are made through rolling of aluminum ingots. The inventory for the process *Sheet panels for BiW* is listed in table 9. The inputs are the materials *Sheet ingots AA6016* and *Sheet ingots 6181-A*, transport and processing. Since the information of the share of the aluminum alloys AA 6016 and 61861-A where not given by Audi, this project assumes a 50/50 share. No specific data was found for the rolling used for the ASF, therefore the Ecoinvent process *Section bar extrusion, aluminum /RER U* where used. This process includes all the steps in semi-fabrication, material loss and transport to the plant as well as infrastructure.

Table 9: Inventory for the process: *Sheet panels for BiW.*

Input	Amount	Unit	Source
Sheet ingots (AA6016)	0.5	kg	
Sheet ingots (6181-A)	0.5	kg	
Transport, freight, lorry > 32 metric ton	0.54	tkm	[32]
Section bar extrusion, aluminium/ RER U	1	kg	[32]
Output			
Sheet panels for BiW	1	kg	

5.3.2 Production of Extruded Sections for Body-in-White

The inventory for the process *Extruded sections for BiW* is given in table 10. The inputs are *Extrusion ingots (AA 6014)*, transport and processing. The output is *Extruded sections for BiW*. The extrusion parts of the ASF is made by the extrusion technique known as hydroforming[17]. Since no data where available for this specific technique, the Ecoinvent process *Section bar extrusion, aluminum /RER U* where used.

Table 10: Inventory for the process: *Extruded sections for BiW.*

Input	Amount	Unit	Source
Extrusion ingots (AA 6014)	1	kg	
Transport, freight, lorry > 32 metric ton	0.72	tkm	[32]
Section bar extrusion, aluminium/ RER U	1	kg	[32]
Output			
Extruded sections for BiW	1	kg	

5.3.3 Production of Cast Parts for Body-in-White

The inventory for the process *Cast parts for BiW* is listed in table 11. The inputs are Cast ingots (Aural-2), transport, infrastructure and processing. The infrastructure is represented trough the Ecoinvent process *Aluminum casting facility, construction, RER, U.* The Aluminum Automotive Manual[17] reports that the casted parts of ASF is made by a closely controlled vacuum high pressure die casting process High-Q-Cast®. Unfortunately no specific data for the specific casting process were found. The processing is therefore represented through the Ecoinvent process *Casting, brass (CH) processing, U.*

Table 11: Inventory for the process: *Cast parts for BiW.*

Input	Amount	Unit	Source
Cast ingots (Aural-2)	1	kg	
Transport, freight, lorry > 32 metric ton	0.095	tkm	[32]
Aluminum cast. facility, construction, RER, U	1.5*10-9	kg	[32]
Casting, brass (CH), processing, U	1	kg	[32]
Output			
Cast parts for BiW	1	kg	

5.3.4 Aluminum Scrap Ingots from Closed-loop Recycling

As stated previously, the joining techniques of the three parts are the same for all three scenarios. This means that the inputs for BiW production are the same, and seen in figure 9. The 3 different parts however, are made from different input materials. For the second scenario, the input is sorted scrap from old BiWs. This means that the processes *Sheet panels for BiW closed-loop*, *Extruded sections for BiW closed-loop* and *Cast parts for BiW closed-loop* have the same input, namely *Aluminum scrap, treated closed-loop.* This process is designed for this project, and the inputs and outputs are listed in table 10.

The output is *Aluminum scrap, treated closed-loop*, and the inputs are discussed below. The processes *Shredding, ELVs* and *Laser-induced breakdown spectroscopy (LIBS), metal scrap sorting* where made for SupLight. The process *Collection of old BiWs for closed-loop* is designed for this project and includes only transport. The process *Melting of aluminum scrap* is also designed for this project, based on the calculations found in appendix A2. Due to lack of data, the cleaning of scrap is omitted.

Table 12: Inventory for the process: *Aluminum scrap, treated closed-loop.*

Input	Amount	Unit	Source
Collection of old BiWs for closed-loop	1	p	
Shredding, ELVs	1	kg	[33]
LIBS, metal scrap sorting	1	kg	[33]
Melting of aluminum scrap	1	kg	[37]
Output			
Aluminum scrap, treated closed-loop	1	kg	

5.3.5 Aluminum Scrap Ingots from Open-loop Recycling

As stated before, the fabrication of the BiW from the three different types of parts are the same for all three scenarios. This chapter will only explain the inventory parts that differ from the first and second scenario. For the third scenario, the input is sorted scrap from ELVs, *i.e* open-loop recycling.

This means that the processes *Sheet panels for BiW open-loop*, *Extruded sections for BiW open-loop* and *Cast parts for BiW open-loop* have the same input, namely *Aluminum scrap, treated open-loop*. This process is designed for this project. As seen from table 13, the only input that differs from scenario 2, is the process *Aluminum scrap, shredded and sorted* and *Collection of old BiWs for open-loop*. *Aluminum scrap, shredded and sorted* is discussed in more detail below. *Collection of old BiWs for open-loop* contains transport, which is discussed in appendix A2. The processes *Aluminum scrap, shredded and sorted* and *Laser-induced breakdown spectroscopy (LIBS), metal scrap sorting* where made for SupLight.

Table 13: Inventory for the process: *Aluminum scrap treated open-loop*.

Input	Amount	Unit	Source
Collection of old BiWs for open-loop	1	p	
Aluminum scrap, shredded and sorted	1	kg	[33]
LIBS, metal scrap sorting	1	kg	[33]
Melting of aluminum scrap	1	kg	[37]
Output			
Aluminum scrap, treated open-loop	1	kg	

The inventory for the process *Aluminum scrap, shredded and sorted* was designed for Suplight[33] and is shown in table 14. 10% of the shredded ELVs is assumed to be aluminum, and the inputs and outputs associated with the different separation techniques are allocated to this share.

Table 14: Inventory for the process: *Aluminum scrap, shredded and sorted*

Input	Amount	Unit	Source
Shredding, ELVs	100	kg	[33]
Air separation, per ton shredded material	100	kg	[33]
Magnetic sorting, non-ferrous material mix	100	kg	[33]
Sink-float separation, material mix, sg 2.1	45	kg	[33]
Sink-float separation, per t scrap, sg 3.1	45	kg	[33]
Eddy current separation, magnetic scrap	39	kg	[33]
Output			
Aluminum scrap	10	kg	[33]
Mat. mix excl. alu., shredded and sorted	90	kg	[33]
Disposal, aluminium in car shredder residue	0.145	kg	[33]
Zinc in car shredder residue	0.145	kg	[33]
Steel in car shredder residue	0.145	kg	[33]
Waste plastic, mixture (waste treatment)	1.015	kg	[33]
Waste glass, (waste treatment)	0.435	kg	[33]
Waste rubber, unspecified (waste treatment)	0.87	kg	[33]

6 Results and Discussion

This section presents the results obtained from the impact assessment performed in the present project. First, results for the three scenarios are presented, one by one, which includes results for the different life cycle stages for each scenario and an investigation of the production steps for each scenario. A study on which parts of the life cycle that contributes to impacts for the different categories is performed, as well as the origin of their contributions. The three scenarios are later compared to each other. This is done by assigning the scenario with the largest impacts, a value of 100%, and the other two scenarios values relative to that. The scenarios are compared on a life cycle stage basis, and the scrap treatment for scenario 2 and 3 is compared.

The impact assessment in this study provides a large amount of results. There are many impact categories and process contributions that would benefit from further investigation and discussion. However, this study focuses on those that is most interesting for the goals of the current project.

The characterized result for each scenario is given below. The results shows which of the life cycle stages for the BiW that contributes most to the total environmental burden of each category. In order to get characterized results the total environmental burden for each category is set to 100%. The respective share for each life cycle stage is assigned their share of the total environmental burdens.

6.1 Scenario 1: Primary Aluminium

This section presents the results for scenario 1, BiW produced from primary aluminum. The results are given in numbers in Appendix B1.

6.1.1 Total Life Cycle

Figure 11 shows the characterized results for the environmental impacts of the different life cycle stages for the BiW produced from primary aluminum, *i.e.* scenario 1 which is the reference scenario for the other two scenarios.

BOL includes the activities concerning the production of the BiW, from raw material extraction, production of sheet, extrusion and cast ingots, production of the parts to assembly of BiW. MOL is the use of the vehicle.

EOL is the collection of the ELVs and transport to ELV treatment facility. Since the current project uses the cut-off approach, contributions from scrap treatment, transport and collection is located in BOL. This is why no contributions is seen for EOL in figure 11.

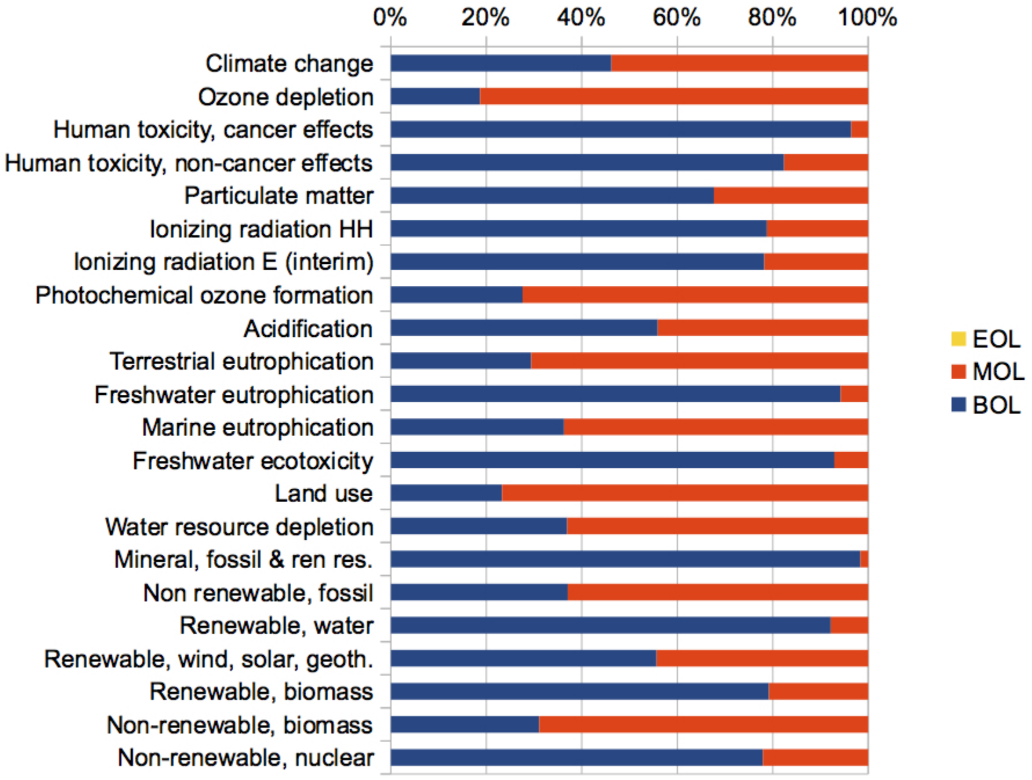

Figure 11: Characterized results for the different life cycle stages of scenario 1(reference scenario).

Figure 11 shows that for the impact categories, human toxicity, cancer and non-cancer effects, freshwater eutrophication, freshwater ecotoxicity, mineral, fossil and renewable resource depletion the BOL stage dominates the impacts, by over 80% of the total number. For the impacts to human toxicity, cancer effects, backward tracing shows that red mud from bauxite digestion is the main origin of the contributions. For the impacts in the freshwater eutrophication category, backward tracing shows that the contributions main origins from spoils from hard coal and lignite mining.

For ozone depletion the MOL stage dominates the impacts, by over 80% of the total number. Ozone depletion contributions stems from crude oil production for petrol.

The share of the impact in the climate change category is about 45% of the impact from BOL, and 65% from MOL. The fact that the BOL has such a large share of the impacts is likely due to the energy intensive electrolysis step in the primary production of aluminum. Backward tracing of the process contributions confirms that the main contribution originate from electricity production for BOL. The main contributions to climate change impacts in MOL originate from petrol use.

Cumulative Energy Demand (CED) through the life cycle of the BiW in scenario 1 is 74 883 MJ (20 800 kWh). In both BOL and MOL non-renewable fossil fuel dominates the CED. 40% of the total CED is from BOL, and 60% from MOL. Backward tracing shows that this origins from electricity used for production of primary aluminum in BOL, and crude oil production for petrol used in MOL.

6.1.2 Beginning of Life

For further investigation of the production of the BiW, figure 12 shows the contributions from the different steps in the production of the BiW.

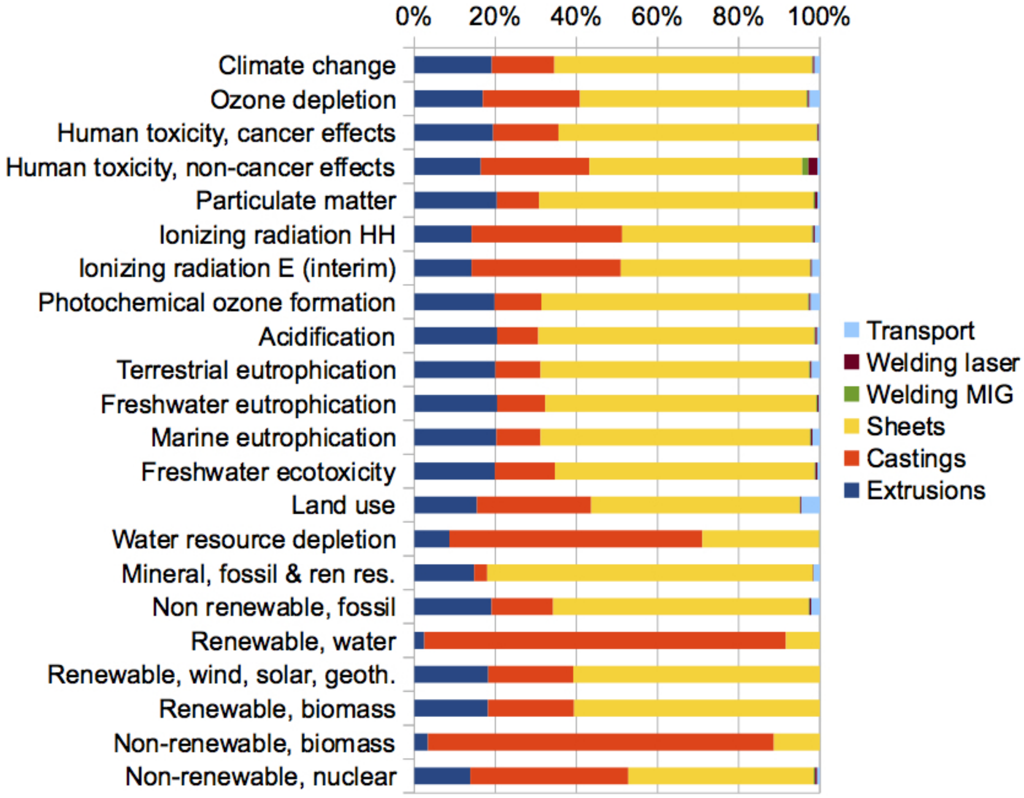

Figure 12: Results for the processes in the production of the BiW for scenario 1 (reference scenario).

It can be seen in figure 12 that the production of the three parts; castings, sheets and extrusions is responsible for above 90% of the impacts in all categories. This means that transport of the parts to and from the different facilities is less important. The same is true for the assembly of the BiW by welding. Most of the contributions for the production of the parts origins from the production of primary aluminum.

6.2 Scenario 2: Closed-loop Recycling

This section presents the results for scenario 2, BiW produced from closed-loop recycled BiWs. The results are given in numbers in Appendix B2.

6.2.1 Total Life Cycle

Figure 13 shows the characterized results for the environmental impacts of the different life cycle stages for the BiW produces from closed-loop recycled BiWs, *i.e.* scenario 2.

In this case BOL includes the activities concerning the production of the BiW, from collection of EOL BiWs, transport, shredding, sorting by LIBS, production of sheet, extrusion and cast parts, as well as assembly of BiW. MOL and EOL is the same as for scenario 1.

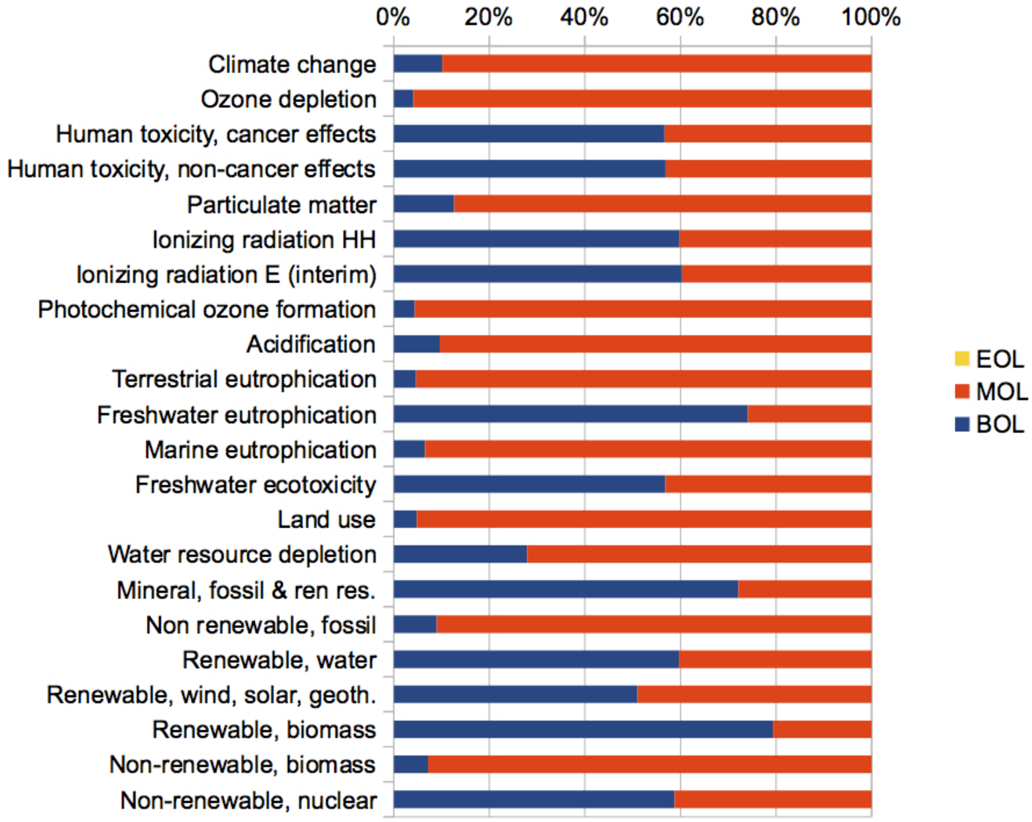

Figure 13: Characterized results for the different life cycle stages of scenario 2, closed-loop recycling.

Figure 13 shows that MOL dominates for most impact categories, with some exceptions. About 20% of the impacts to climate change occurs in BOL and 80% in MOL. This differs significantly from the results for scenario 1, where the share was 45% to 65%, respectively. This shows that the primary production of aluminum has larger contributions than the production with closed-loop recycled BiWs as input.

For human toxicity, cancer and non-cancer effects, ionizing radiation E (interim), freshwater eutrophication, mineral, fossil and renewable resource depletion, the contributions splits between BOL and MOL with shares ranging from 50-70%. Backward tracing of the contributions to mineral, fossil and renewable resource depletion shows that a large share of them origins from mining of zinc.

CED through the life cycle of the BiW in scenario 2 is 50 743 MJ (14 095 kWh). As for scenario 1, the CED is dominated by non-renewable fossil fuel. Almost 90% of the total CED is from MOL. Backward tracing shows that this origins from crude oil production for petrol.

6.2.2 Beginning of Life

The results for the production of the BiW for scenario 2 is shown in figure 14. As for scenario 1, the three types of parts used in the BiW represents the largest share of the impacts in all categories.

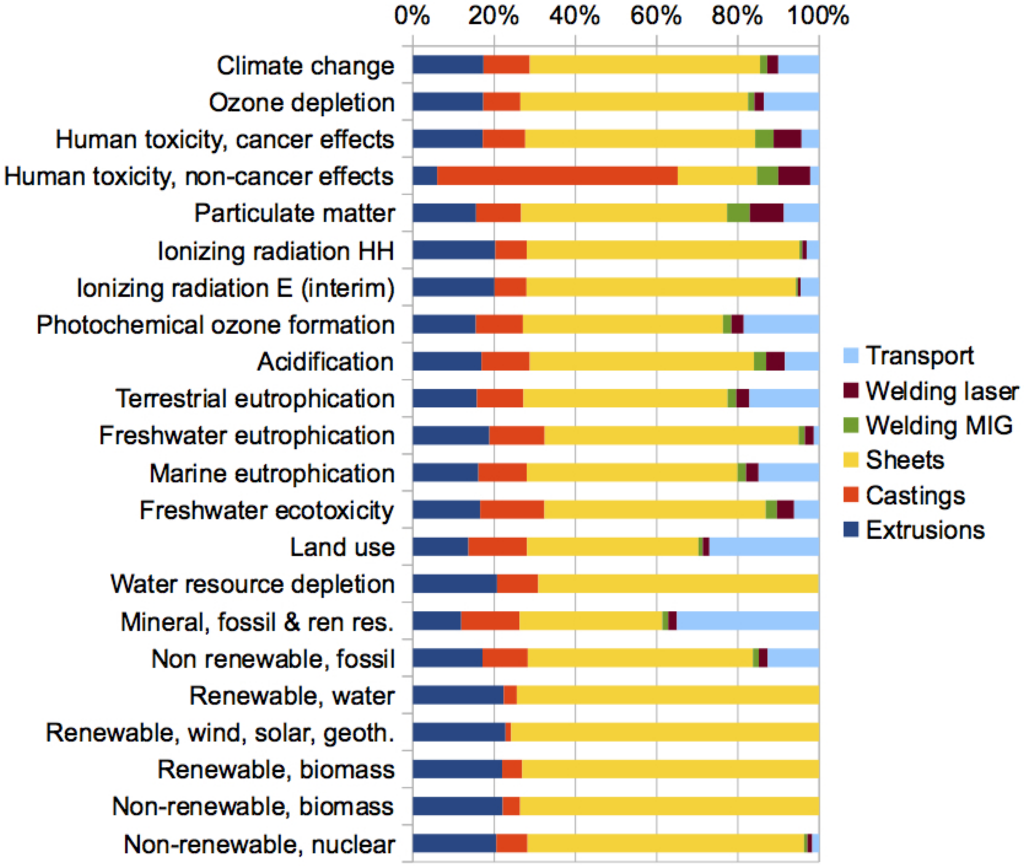

Figure 14: Results for the processes in the production of the BiW for scenario 2, closed-loop recycling.

However, it can be seen from figure 14 that the transport represents a larger share in several of the impact categories for scenario 2, compared to scenario 1. The reason for this is that the contributions from sheets, castings and extrusions production are smaller in scenario 2, and therefore the transport contributes to a larger share of the total impact.

6.2.3 Scrap Treatment

Figure 15 shows the impacts from the scrap treatment procedures in scenario 2. This includes collection of old BiWs for recycling, *i.e.* transport to the different facilities, shredding of BiWs, sorting of scrap by LIBS and melting of scrap.

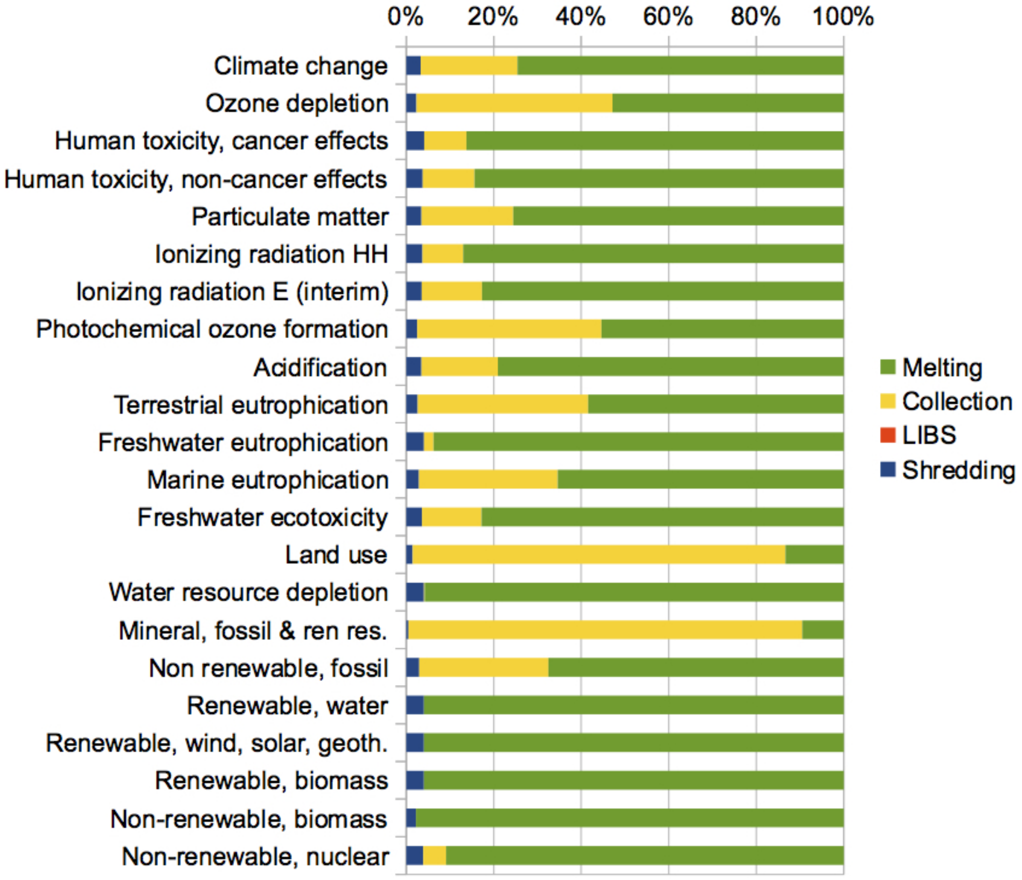

Figure 15: Scrap treatment results for scenario 2, closed-loop recycling.

It can be seen in figure 15 that melting of the scrap is the largest contributor to almost all categories, with exceptions for land use and mineral, fossil and renewable resource depletion. The dominance of melting in CED is due to the energy used for melting the aluminum scrap. The sorting by LIBS has negligible impacts for all impact categories.

Collection consists of transportation of the parts to and from the facilities. The impacts to land use and mineral, fossil and renewable resource depletion may be traced back to the use of land for road construction and fuel combustion respectively.

6.3 Scenario 3: Open-loop Recycling

This section presents the results for scenario 3, BiW produced from open-loop recycling of ELV scrap. The results are given in numbers in appendix B3.

6.3.1 Total Life Cycle

Figure 16 shows the characterized results for the environmental impacts of the different life cycle stages of the BiW produced from open-loop recycled ELV scrap, *i.e.* scenario 3.

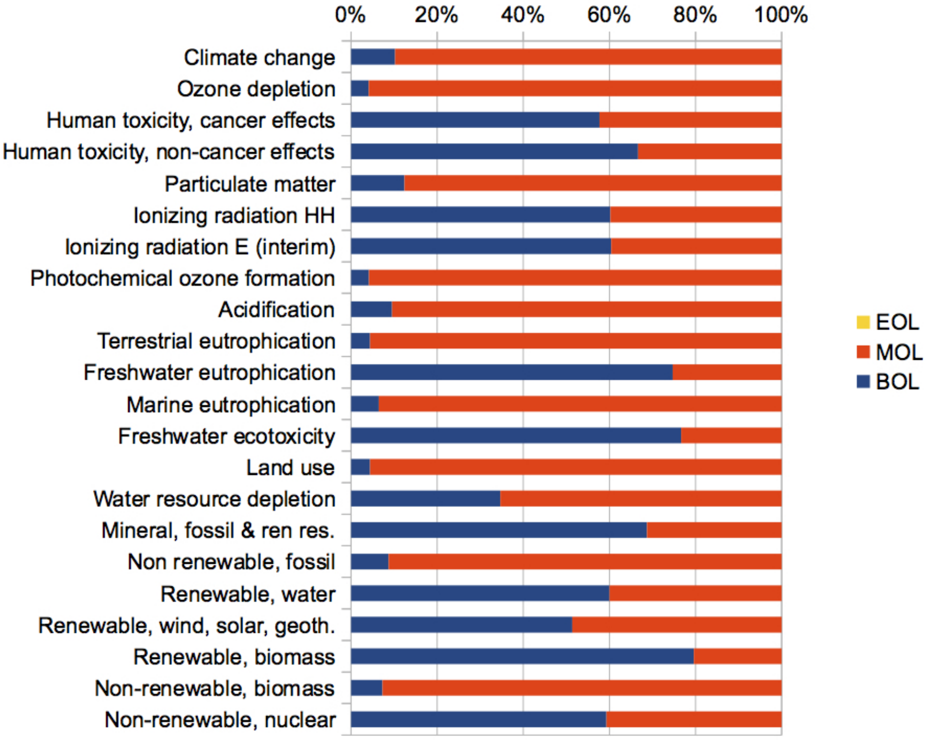

Figure 16: Characterized results for the different life cycle stages of scenario 3, open-loop recycling.

BOL include the activities concerning the production of the BiW, from the collection of the ELVs, transport, shredding, sorting trough the steps discussed and shown in figure 3, as well as sorting by LIBS. The production of the sheet, cast and extrusion parts, and the assembly of the new BiW are also included. The MOL and EOL stage are the same as for scenario 1.

Figure 16 shows that MOL dominates for most impact categories, which is the same result as for scenario 2. This indicates that primary production of aluminum has more impact than both closed-loop and open-loop recycling. There are small differences in figure 13 and 16. This is due to the fact that the only thing separating the two scenarios is the larger amount of transport in scenario 2, and the sorting steps in scenario 3. This gives slightly larger numerical values for the contributions in ozone depletion and land use for scenario 2, which again is due to the larger amount of transport in scenario 2.

For scenario 3, the values in climate change is slightly larger, and twice as large for freshwater ecotoxicity. Backward tracing shows that the increased contributions to freshwater ecotoxicity is due to the waste treatment of zinc in car shredder residue.

CED through the life cycle of the BiW in scenario 3 is 50 629 MJ (14 064 kWh). As for scenario 1 and 2, the CED is dominated by non-renewable fossil fuel, and almost 90% of the total CED is from MOL. Also in this case, backward tracing shows that impacts originate from crude oil production for petrol.

6.3.2 Beginning of Life

Figure 17 shows the results for the production of the BiW for scenario 3. As for scenario 1, the three types of parts used in the BiW represents the largest share of the impacts in all categories.

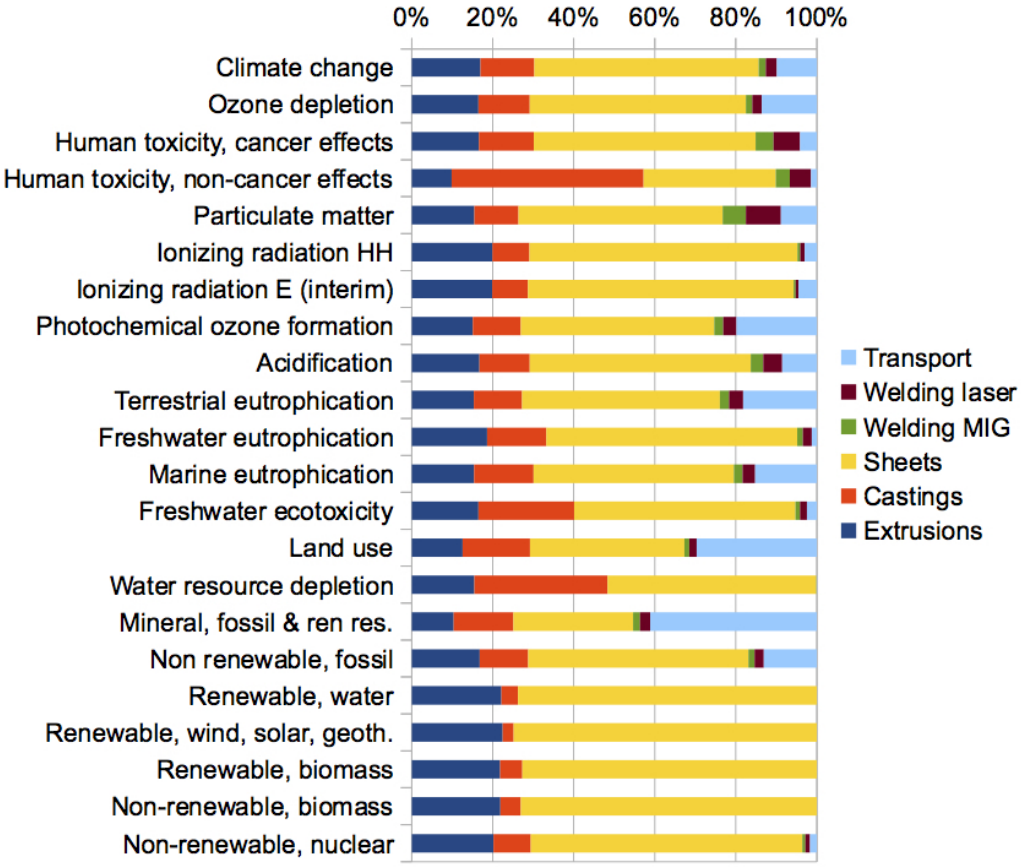

Figure 17: Results for the processes in the production of the BiW for scenario 3, open-loop recycling.

6.3.3 Scrap Treatment

Figure 18 shows the impacts from the scrap treatment procedures in scenario 3. This includes collection of ELV scrap, *i.e.* transport to the different facilities, shredding and sorting and melting of scrap. Sorting of scrap involves the common sorting techniques used for separating ELV scrap as seen in figure 3, as well as LIBS for further sorting.

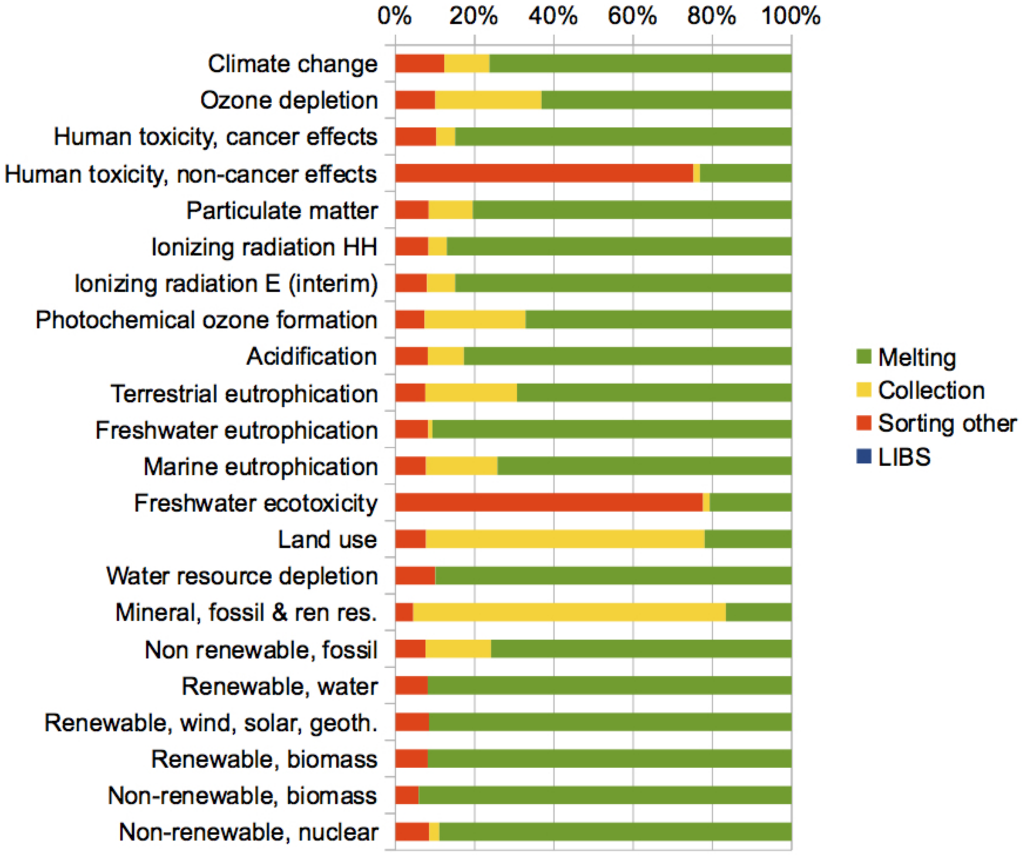

Figure 18: Scrap treatment results for scenario 3, open-loop recycling

It can be seen in figure 18 shows that the melting of scrap is responsible for most of the impacts from scrap treatment, as is the case for scenario 2. The exceptions are human toxicity, non-cancer effects, freshwater ecotoxicity, land use and mineral, fossil and renewable resource depletion. Backward tracing shows that the contributions to human toxicity, non-cancers effects stems from waste treatment of zinc in car shredder residue. This also causes a large share of the impacts to freshwater ecotoxicity, as already stated. The impacts to land use is due to the need for land for road infrastructure.

The contributions for mineral, fossil and renewable resource depletion are also related to zinc used for coating of steel for construction of buildings, and for production of synthetic rubber used for maintenance of the lorry. Land use is due to the need for land for road infrastructure.

CED is dominated by the melting of scrap, with a small share of the contributions from sorting.

6.4 Comparison

In this section the results from the three scenarios are compared. The results are given in numbers in appendix B4.

6.4.1 Life Cycle of All Three Scenarios

Figure 19 shows the comparison of the total environmental burdens for the entire life cycle of the BiW for all scenarios. MOL and EOL are the same in all three scenarios. The difference is in the aluminum input to the production of the sheet, cast and extrusion parts. The use of scrap aluminum reduces the impacts in all categories except the CED category renewable biomass.

The potential reductions in environmental impacts are largest, over 80%, for human toxicity, cancer effects and mineral fossil and renewable resource depletion. This is due to the fact that the red mud from bauxite digestion is eliminated from the production, and that scenario 2 and 3 uses scrap aluminum instead of extraction from mineral ore.

Figure 19 shows that scenario 2 and 3 has 60% of the impacts to climate change compared to scenario 1. This shows that removing the energy intensive production of primary aluminum is beneficial in terms of climate change impacts.

Freshwater eutrophication and freshwater ecotoxicity also have large potential savings of environmental impacts for scenario 2 and 3. Backwards tracing shows that a large share of the contributions to freshwater eutrophication stems from the mining of coal, used for electricity purposes. The large contributions for freshwater ecotoxicity is due to the red mud from bauxite digestion in the primary production of aluminum.

Ozone depletion, photochemical ozone formation, land use and water resource depletion is the categories with the smallest potential for environmental impact reductions; about 10 to 25%.

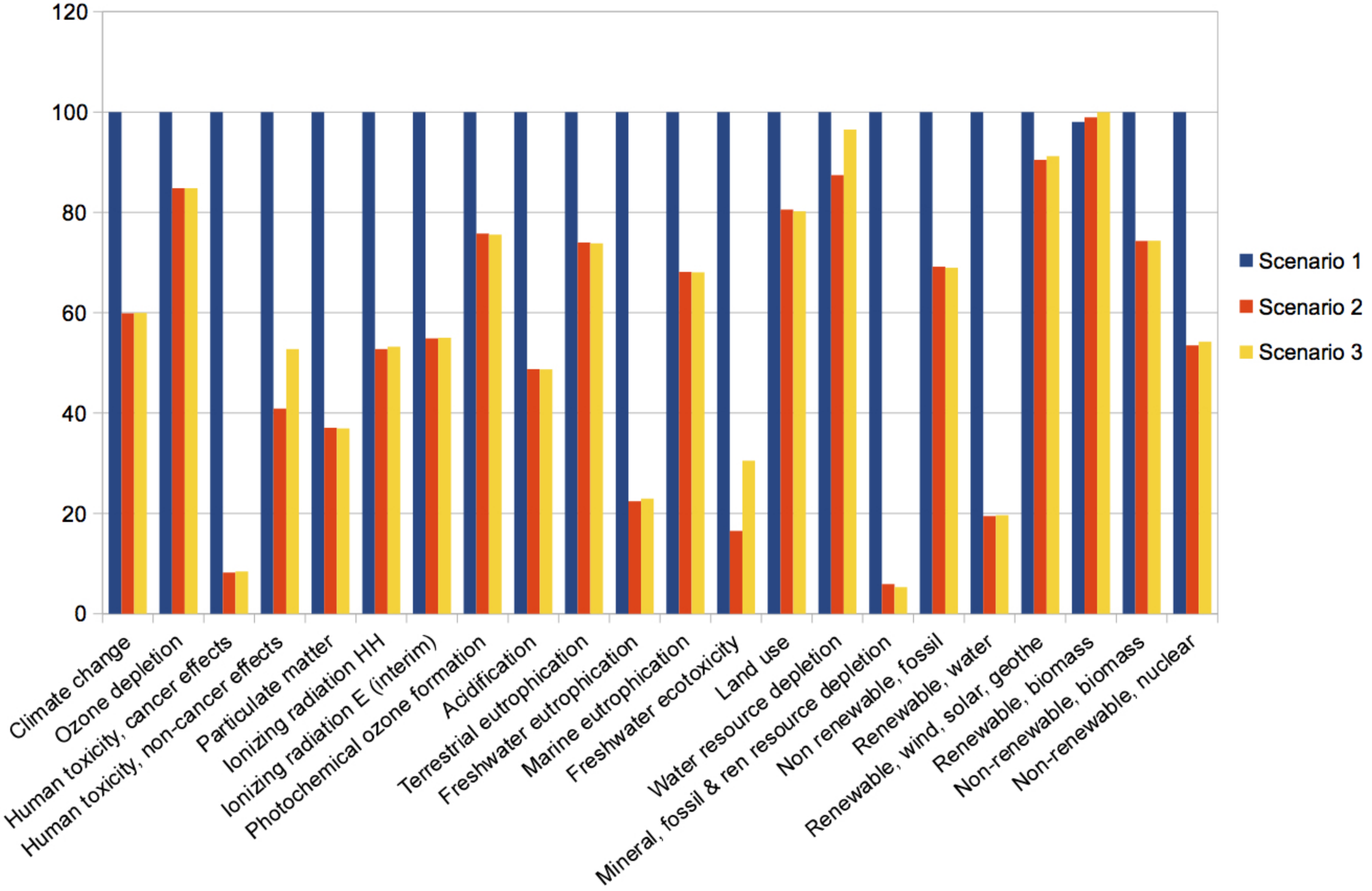

Figure 19: Results for the total life cycle of the BiW for the three scenarios, *i.e.* reference, closed-loop recycling and open-loop recycling.

6.4.2 Closed-loop versus Open-loop Scrap Treatment

Figure 20 compares the treatment of the scrap for scenario 2 and 3, *i.e.* closed-loop and open-loop recycling. The difference between the treatment of the scrap for these two scenarios are the transport and sorting techniques. The melting of the scrap, LIBS and shredding are the same. Scenario 2, has more transport than scenario 3. This is due to the fact that the availability of EOL aluminum BiWs is smaller than the availability of ELVs, and that the EOL BiWs therefore needs to be collected from a larger geographical area. Scenario 3 has more sorting steps than scenario 2.

As can be seen from figure 20, scenario 2 has higher impacts in all categories, except human toxicity, cancer and non-cancer effects, freshwater ecotoxicity and water resource depletion.

The largest difference between the two scenarios is found in the categories human toxicity, non-cancer effects, freshwater ecotoxicity, land use and mineral, fossil and renewable resource depletion. The contributions for these categories have been discussed previously. The contributions to human toxicity, non-cancers effects and freshwater ecotoxicity stems from waste treatment of zinc in car shredder residue. The contributions for mineral, fossil and renewable resource depletion are related to zinc used for coating of steel for construction of buildings, and for production of synthetic rubber used for maintenance of the lorry. Land use is due to the need for land for road infrastructure.

As for the CED, scenario 2 has higher impact in non-renewable fossil fuel, due to more transport. Scenario 3, has larger impacts in the other five CED categories.

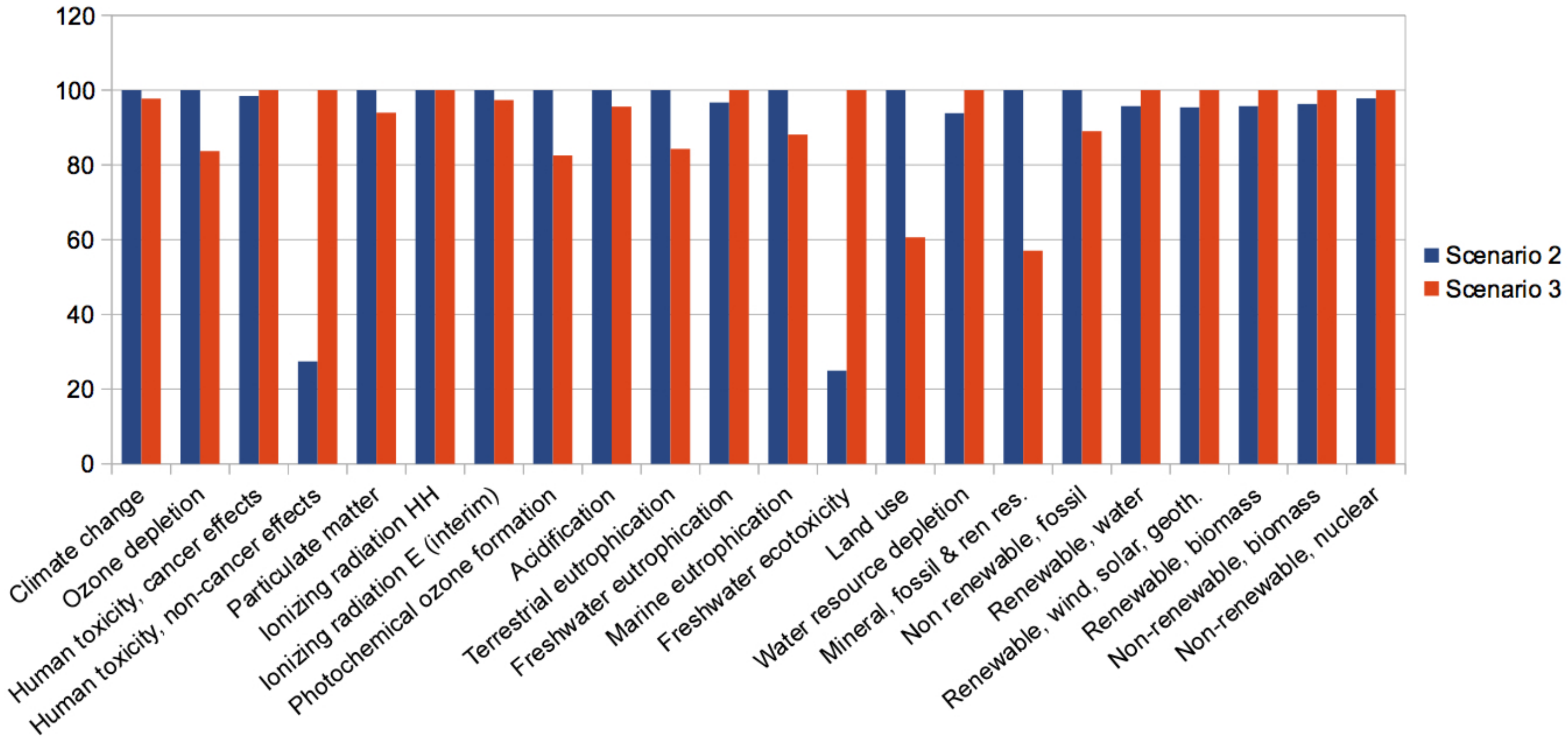

Figure 20: Results for the comparison of scrap treatment for scenario 2 and 3, *i.e.* closed-loop recycling and open-loop recycling.

7 Overall Discussion

This section aims to enlighten the challenges with performing an LCA on the use of recycled aluminum for BiW production. It also addresses the key issues with the use of scrap instead of primary aluminum for BiW production.The problems that must be overcome in order to achieve a successful recycling loop may be divided into two main challenges; the flow and availability of scrap, and the economics of primary versus secondary aluminum. As for the LCA model, the large challenge is the problem of getting acceptable inventory data. These three challenges will be discussed below.

In the current project the product discussed is an aluminum BiW, but the challenges and proposed solutions may be transferred to other high-end aluminum products.

7.1 Aluminum Scrap Flows and Availability

Schlesinger[5] points to the need for a large and recurring supply of metal in order to have a well functioning production of secondary aluminum. It may therefore be argued that the fact that the availability of aluminum BiWs is practically absent today is a weakness of the current study. However, this study primarily aims to investigate the effects of primary versus secondary aluminum BiWs. It is therefore a study of what the future of aluminum recycling may look like, and not status on the present situation. The results from the current project shows that, due to the very energy demanding electrolysis step in the primary production, the energy categories will strongly favor the use of secondary aluminum.

The increased use of aluminum in many products, may during the years to come, give an increase in available aluminum scrap. Figure 21 shows the stock of aluminum in use, and a projection of the future development of the stock. The increased use of magnesium and aluminum in cars, has contributed to increasing the value of recycling as well[5]. These two aspects may lead to more secondary aluminum available in the years to come.

However, it is not only a question of available aluminum scrap in the future. Not all scrap is likely to be suitable for all purposes, in particular a high-end product such as BiW. It is therefore of interest to look at available sources for this specific product, and the alloys involved in it. An extended analysis of potential scrap sources suitable for BiW production is a relevant future step. Investigations on how the properties and product performance

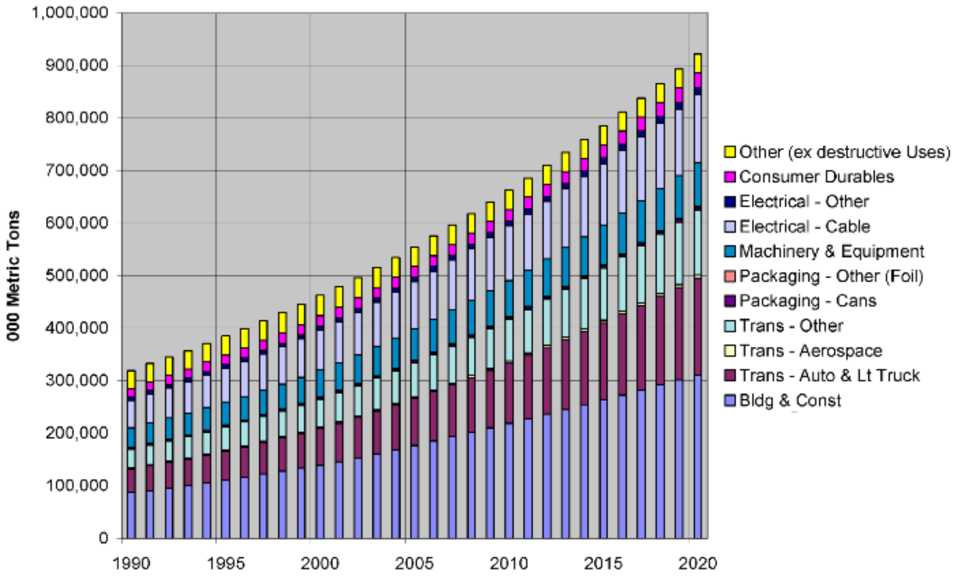

Figure 21: Global Aluminum Product Inventory [35].

is affected by relaxing the purity requirements is also a relevant strategy for making decisions on whether or not a product is suitable for production from secondary aluminum.

7.2 Data Quality

A very common challenge when performing LCAs is to get inventory data with sufficient quality for the processes. This was also the case for the present project. The fact that only energy data where found for LIBS, is a clear weakness. The LIBS is a complex electronic device and it is likely that the impacts to several of the categories would be higher for scenario 2 and 3, if complete inventory data had been available and implemented.

Some other processes also proved difficult to find data for, such as collection of old BiWs. The reason is simply that this is not monitored in an extensive manner today. The solution is a rough estimate on the transport from a collection facility to the treatment facility. The results shows that transport has small impacts compared to the overall scrap treatment impacts. This implies that the uncertainties in the assumptions don't affect the results largely.

Other processes also proved difficult to find data for, like self-pierce riveting, coating of aluminum parts, and cleaning of scrap. Data for processes containing these steps where found, but allocation of contributions to the specific tecniques proved difficult. These processes was therefore left out of the model.

In other cases general data where found, but not for the specific production processes used for the ASF. This was the case for the production of the cast, extruded and sheet parts for the BiW, as well as the joining techniques for the BiW. The LCA model developed in the present project would benefit from specific data for production processes provided by industry.

Another challenge regarding data quality in LCA is the age of the data. Most of the data used in this study is taken from Ecoinvent, an LCA database who recently was updated (May 2013). However, the metal industry is continuously striving towards less energy demanding production processes, and small changes are done all the time. This means that the data input in the present study should be continuously revised and updated in the future.

7.3 Economical Aspects

7.3.1 Costs of Secondary and Primary Aluminum

As previously stated, one of the key prerequisite for the present project and its relevance in the future is that the price on aluminum scrap goes down, or that the price of primary aluminum goes up. However, there is no guaranty that this will happen.

Aluminum products, with some exceptions, have a relative long lifetime, and the time delay before the products reaches EOL is therefore relatively long. However as the use of aluminum increases, so will, in time, the amount of available scrap. This may lead to decreased prices of aluminum scrap. As the most available sources of primary aluminum is exploited, the resources and energy, and thereby also the costs of mining will increase [5]. If this happens, it will lead to increased prices of primary aluminum. Moreover, this will most likely motivate for increased use of secondary aluminum. In terms of energy, the window of operation for treating scrap will grow larger.

7.3.2 Costs of Scrap Treatment

One aspect of the comparison of secondary and primary aluminum BiW is the cost of scrap sorting. Although LIBS is an available technology today, it is not on largely implemented on industrial scale. The large investment costs for LIBS makes it too expensive to be attractive with the prices of aluminum today, but this may change if the predictions discussed earlier proves right. However, there are several alternatives to LIBS on the marked. There is no guaranty that LIBS will be the technology used for alloy sorting in the future.

Another expensive problem of open-loop, and closed-loop recycling is the cost of having a large stock of scrap available as input. This involves a large use of land which, depending on where it is situated, may be costly. For many companies in the scrap trading business, time is also a very important aspect.

It is also a question of the cost of collection of suitable scrap. Maintaining a large enough, and reliable source of suitable scrap may become expensive. This argues that the most likely future scenario is that only a share of the aluminum inputs to production of high-end products comes from scrap sources.

7.3.3 Costs of Steel versus Aluminum BiWs

Up until now, only the price of aluminum, *i.e* primary and secondary aluminum has been discussed. However, most BiWs today are produced from steel. It is therefore relevant to look at the production costs for both steel and aluminum BiWs, and compare these. There have been studies comparing the use of steel and aluminum for BiW production[36]. The largest trigger for increased use of aluminum in vehicles is, however, the costs of increasing taxes and regulations on non-environmental friendly emissions and wastes. The car manufacturers today strive towards, or at least should strive towards, making lighter and more eco-friendly cars. This is done by decreasing emissions, *i.e.* decreasing weight. It is likely that the producers that are able to make this shift in time will be most successful in the future.

8 Conclusion

The present study has provided a comparison of the environmental performance for an aluminum BiW made from three different material inputs, *i.e.* primary aluminum (scenario 1), closed-loop recycled old BiWs (scenario 2) and open-loop recycled ELVs scrap (scenario 3). From the results it is clear that scrap is the best input choice. This is reflected in the contributions for the environmental impacts categories for the three scenarios when they are compared. In fact, scenario 2 and 3 scores better than scenario 1 in all categories except the CED category renewable, biomass. The differences between scenario 2 and 3, however, are relatively small in most environmental impact categories.

It should be mentioned that there are large challenges with the input data to the present LCA model. It may be argued that the missing data may be the reason for the small differences between scenario 2 and 3. As previously stated, the only thing that separated scenario 2 from scenario 3 is the amount of transport and the ELVs scrap sorting steps. A reasonable assumption is that the difference between these two scenarios will change if all inputs where added. This means input like; land use for storage of scrap, electricity for heating of manufacturing plants and other space, chemicals used for sorting equipment etc.

It is also possible that the fact that only electricity use is implemented for LIBS affects the ratio between scenario 1, 2 and 3. As already pointed out, LIBS is a complex technique with a large share of electronics. A complete set of inventory data for the process of sorting with LIBS will most likely affect the results in several impact categories.

The current project also discusses several aspects and challenges regarding the use of scrap as input to BiWs. This is necessary as the project is based on assumptions and projections on what the future might look like.

The first challenge is the availability of suitable scrap. An fundamental prerequisite for using scrap as input to a production process is a recurring supply of suitable scrap. As the use of aluminum in the world today is large and increasing, it may be argued that the availability of suitable scrap will improve in the future.

The second challenge is that of scrap economy and how this varies with time and politics. The variations in price of secondary and primary aluminum also leads to variations in the window of operation in terms of scrap treatment. It is clear that the attractiveness of using scrap is closely related to price, and therefore will vary over time.

The third challenge is sufficient treatment of the scrap for obtaining an acceptable scrap quality. This must be done while ensuring the profit of all the actors in the life cycle of aluminum scrap.

The largest competitor to aluminum BiW is the most common BiW type today, which is steel BiW. As the taxes and regulations on emissions is increasing in several parts of the world, the weight reduction associated with the use of aluminum in the automotive industry will promote aluminum as an automotive material.

9 Future Work

The present project is based on assumptions regarding the future of aluminum scrap economy and use. As the years go these assumptions will either prove right or wrong. If the projections made regarding availability and price of aluminum scrap proves right, the expansion of this model for use on other high-end aluminum products is relevant. It may then be a valuable tool for decision-making if the economy allows for more advanced sorting and treatment of aluminum scrap for wrought to wrought recycling.

As stated earlier, the quality of the results in some stages suffers from shortage on acceptable and available data and other information on the processes involved. The model could be significantly improved by better data on all the individual processes included in the analysis. This is especially true for the processes involved in dealing with aluminum scrap, from collection to sorting and treatment.

LIBS is used for sorting the scrap in the developed model. However, LIBS is not a new technology, and the challenges with it has stopped it from having an fast entry into the aluminum industry. There are several available technologies for alloy sorting of aluminum scrap, for instance refining techniques that involves remelting and chemical treatment of scrap. The comparing of environmental performance for physical and chemical methods for treating scrap is highly dependent on the energy source for electricity used. This is also an aspect that would benefit from further investigations.

This project has investigated three scenarios; production from primary aluminum, closed-loop recycled aluminum and open-loop recycled aluminum. An interesting follow up would be to investigate the environmental impact of scenarios where the material input is a mixture of primary and secondary aluminum. This has been left out of the present study, but would be an interesting and necessary step towards a more realistic model.

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Appendices

Appendix A Model Assumptions

A.1 Transport

Several processes in this model requires input of transport from one facility to another. The process used is the Ecoinvent process *Transport, freight, lorry* $>$ *32 metric ton, EURO 5.* In order to maintain transparency of the work done in this project, the transport assumptions will be addressed separately in this section.

This transport process includes the entire life cycle of transport. This means that life cycle components such as road infrastructure, construction of roads, expenditures, operation of road infrastructure, land use etc. have been allocated on a tonne kilometer (tkm) basis. EURO5 refers to a specific category of vehicles in terms of emission standards.

For scenario 1, the process *Aluminum, primary, at plant/RER U* accounts for all inputs and outputs, including transport to where the cast/extrusion/rolling billets are produced. RER means that the data is from Europe, and U means that this is a unit process, not a system process.

There are five transport stages that needs to be estimated for scenario 1, as illustrated in figure 22 and listed in table 15. First the transport of the cast part from alloy/part manufacturing to car manufacturer (1). Then the extrusion alloy to the extrusion house (2), and the sheet parts from the cast/rolling house to the car manufacturer (3). Both the casting of the cast parts and the rolling of the sheets is assumed to be preformed at the same location as the alloy casting. The extrusion parts are transported to the car manufacturer (4). The last transport stage is the transport of the car to the car dealer (5). The manufacturer of the parts and the car is assumed to be placed in Germany. The car is assumed to be sold in Norway.

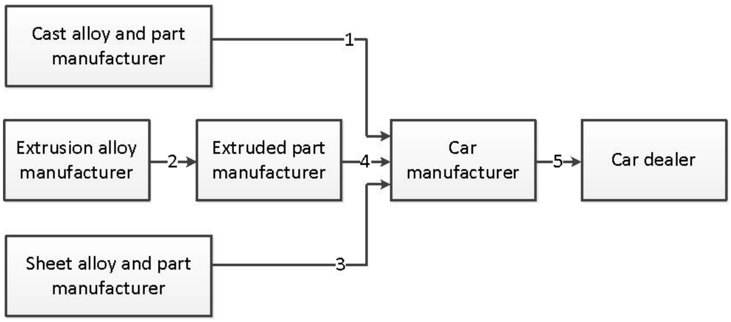


Figure 22: Transport steps for scenario 1.

Table 15: Transport assumptions for scenario 1.

		Dist. (km)	Weight (kg)	Amount (tkm)
1	Cast al./part man. to car man.	95	33.66	3.20
2	Ex. alloy to part man.	384	27.54	10.58
3	Sheet al./part man. to car man.	540	91.8	495.72
4	Ex. part to car man.	720	27.54	19.83
5	Car man. to car dealer	2000	153	306

For scenario 2, where the input to production is old BiWs (closed-loop recycling), the transport is slightly different. The transportation steps for scenario 2 is illustrated in figure 23 and listed in table 16. Here, the transport from the scrap dealer to the collection facility is the first stage (1). Then the scrap is transported to the sorting and treatment facility (2). The scrap is sorted and transported from the recycling facility to the part manufacturers (3,4 and 5).

After these stages, the transport steps are the same as for scenario 1. From part manufacturers to car manufacturer (6,7 and 8), and from car manufacturer to car dealer (9).

One of the largest transportation distances in this scenario is the transport from the scrap dealer to collection and from collection to the recycling facility. Due to the limited amount of available EOL BiWs, the collection must be from a large geographical area. Europe is chosen and an average distance from scrap dealers all over Europe to a collection facility in Germany is used.

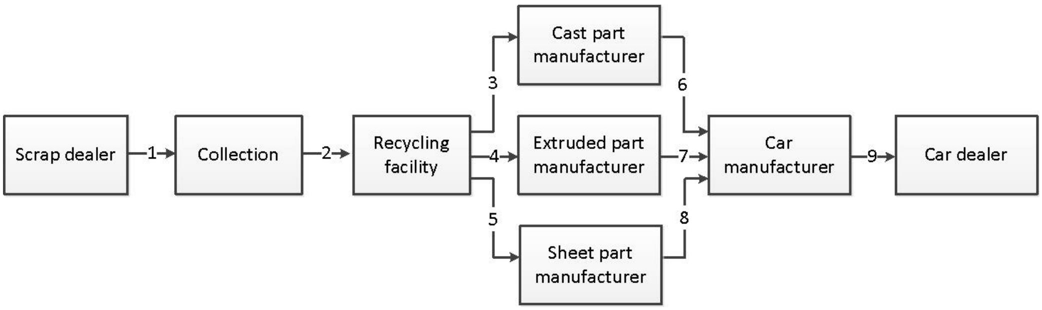


Figure 23: Transport 2 steps for scenario 2 and 3.

Table 16: Transport assumptions for scenario 2.

		Dist. (km)	Weight (kg)	Amount (tkm)
1	Scrap dealer to collection	500	153	76.5
2	Collection to rec. fac.	1500	153	229.5
3	Rec. fac. to cast part manu.	614	33.66	20.67
4	Rec. fac. to ex. part manu.	252	27.54	6.94
5	Rec. fac. to sheet part manu.	16	91.8	14.69
6	Cast part man. to car man.	95	33.66	3.20
7	Ex. part to car man.	720	27.54	19.83
8	Sheet part man. to car man.	540	91.8	495.72
9	Car man. to car dealer	2000	153	306

For scenario 3, where the input is aluminum from ELVs (open-loop recycling), the transport steps are almost the same as for scenario 2. The only exception is that there is a higher amount of scrap available, due to the fact that all suitable ELV scrap can be used as input. This means that the collection may be concentrated to a smaller geographical area, like Germany. The steps are seen in figure 23 and table 17, and are as follows. Transport from scrap dealer to collection facility (1). Transport from collection facility to recycling facility (2). Transport from recycling facility to part manufacturers (3,4 and 5). Transport from part manufacturers to car manufacturer (6,7 and 8). Transport from car manufacturer to car dealer (9).

Table 17: Transport assumptions for scenario 3.

		Dist. (km)	Weight (kg)	Amount (tkm)
1	Scrap dealer to collection	500	153	76.5
2	Collection to rec. fac.	500	153	76.5
3	Rec. fac. to cast part manu.	614	33.66	20.67
4	Rec. fac. to ex. part manu.	252	27.54	6.94
5	Rec. fac. to sheet part manu.	16	91.8	14.69
6	Cast part man. to car man.	95	33.66	3.20
7	Ex. part to car man.	720	27.54	19.83
8	Sheet part man. to car man.	540	91.8	495.72
9	Car man. to car dealer	2000	153	306

A.2 Aluminum Scrap Melting

In her master thesis, Gro Gilstad[37] investigated several refining techniques for secondary aluminum by performing an LCA. As well as for this project, the melting of scrap was an important aspect of the modeling, due to the fact that it causes a large share of the impacts from scrap prossessing. The techniques and values chosen for this project is based on the work done by Gilstad[37].

A large range of different melting furnaces exists for melting aluminum scrap. They may be separated into two main groups; electric and fossil-fuel furnaces. Induction furnaces and resistance furnaces are electric, and single-chamber or multiple-chamber furnaces, small-volume melters, rotary furnaces, and holding and dosing furnaces are fossil-fuel based. Most aluminum scrap is melted by the combustion of fossil fuels[5].

Based on literature studies, Gilstad chose an induction furnace without a salt layer as the applied technology.

For finding the energy needed for melting the scrap, Gilstad uses several approaches. One is to use the energy needed for primary production, and take a 5-10% share of that value. This gives an energy need of 0.5-1.5 kWh per kg aluminum melted.

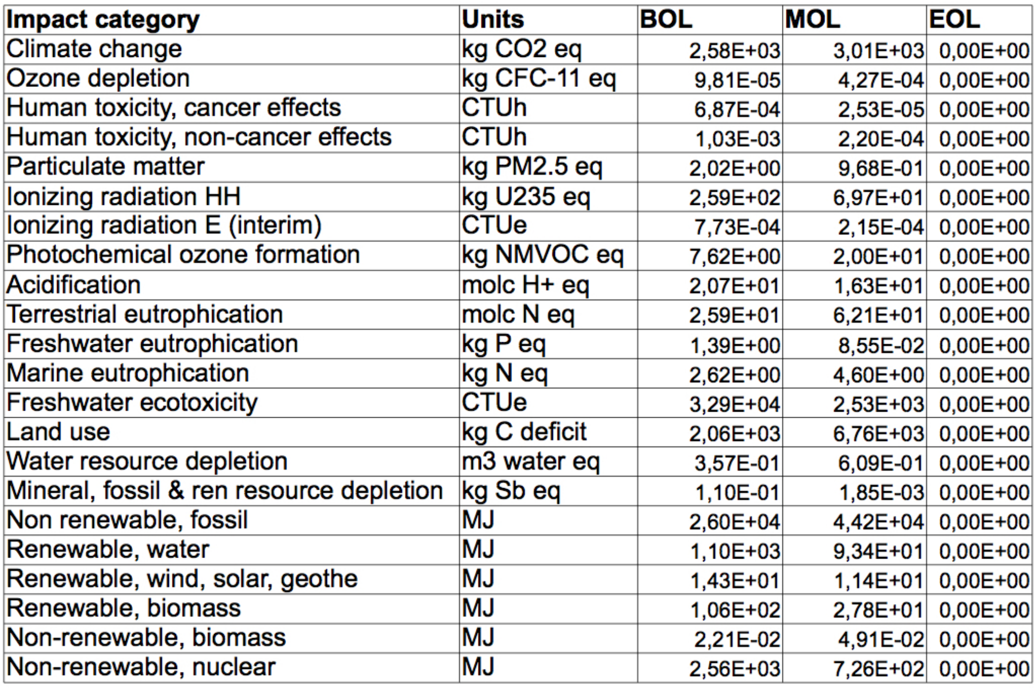
By performing energy calculations,a value of 2.24 kWh per kg aluminum was obtained[37]. This is the energy needed to melt pure aluminum, but the energy use is expected to be lower for aluminum with alloy content.

By communication with Anne Kvithyld at SINTEF Materials and Chemistry in May 2013, Gilstad received information on EU best practice for melting scrap. This value was 0.5 kWh/kg.

Based on the information above, a value of 0.7 kWh/kg was chosen for energy use in melting of scrap, and the same value is applied in this project. Infrastructure was also included trough the process *Aluminium melting furnace/RER/ I U.*

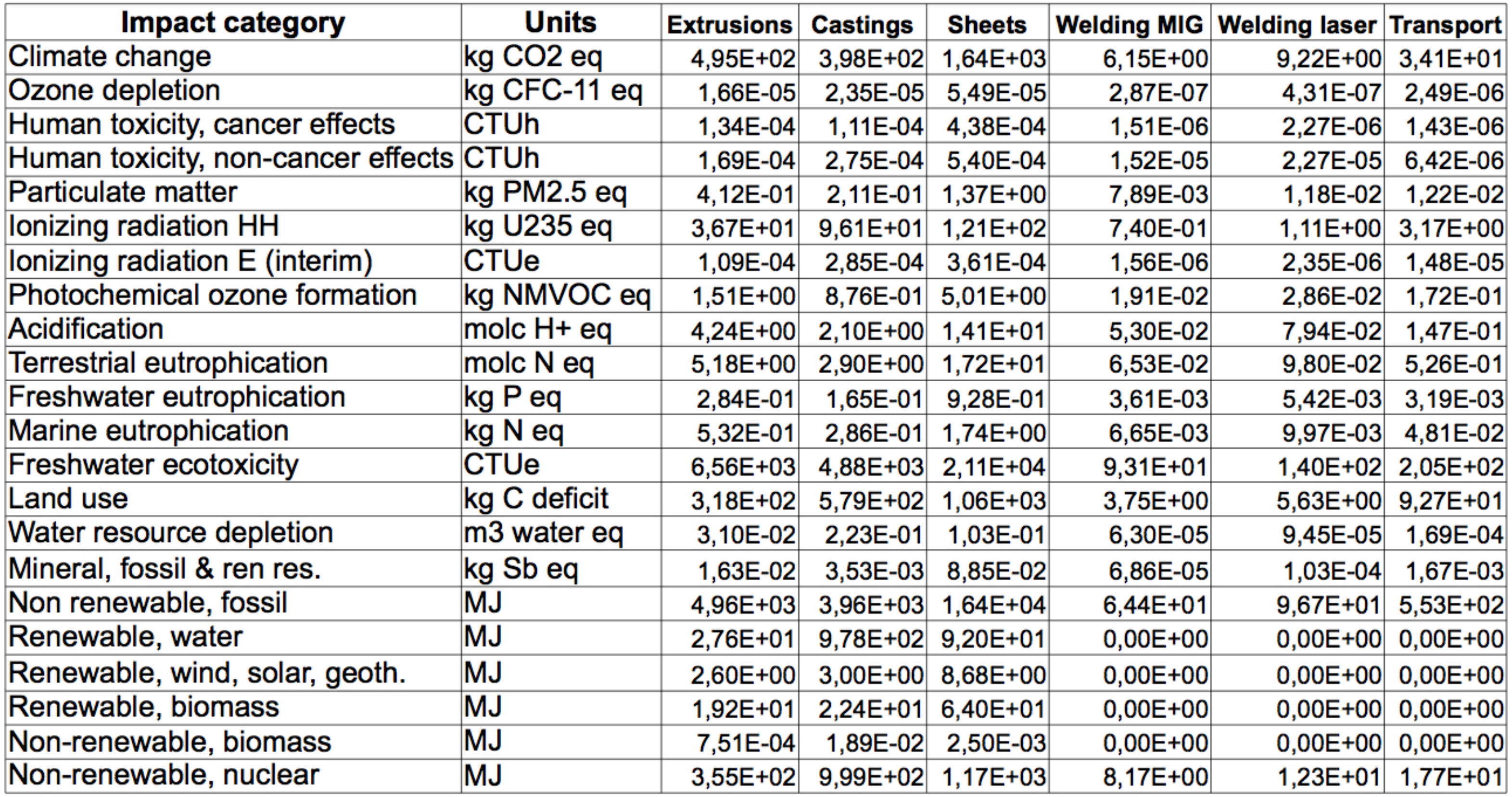
Appendix B Results Tables

B.1 Scenario 1: Primary Aluminum



Impact category	Units	BOL	MOL	EOL
Climate change	kg CO2 eq	2,58E+03	3,01E+03	0,00E+00
Ozone depletion	kg CFC-11 eq	9,81E-05	4,27E-04	0,00E+00
Human toxicity, cancer effects	CTUh	6,87E-04	2,53E-05	0,00E+00
Human toxicity, non-cancer effects	CTUh	1,03E-03	2,20E-04	0,00E+00
Particulate matter	kg PM2.5 eq	2,02E+00	9,68E-01	0,00E+00
Ionizing radiation HH	kg U235 eq	2,59E+02	6,97E+01	0,00E+00
Ionizing radiation E (interim)	CTUe	7,73E-04	2,15E-04	0,00E+00
Photochemical ozone formation	kg NMVOC eq	7,62E+00	2,00E+01	0,00E+00
Acidification	molc H+ eq	2,07E+01	1,63E+01	0,00E+00
Terrestrial eutrophication	molc N eq	2,59E+01	6,21E+01	0,00E+00
Freshwater eutrophication	kg P eq	1,39E+00	8,55E-02	0,00E+00
Marine eutrophication	kg N eq	2,62E+00	4,60E+00	0,00E+00
Freshwater ecotoxicity	CTUe	3,29E+04	2,53E+03	0,00E+00
Land use	kg C deficit	2,06E+03	6,76E+03	0,00E+00
Water resource depletion	m3 water eq	3,57E-01	6,09E-01	0,00E+00
Mineral, fossil & ren resource depletion	kg Sb eq	1,10E-01	1,85E-03	0,00E+00
Non renewable, fossil	MJ	2,60E+04	4,42E+04	0,00E+00
Renewable, water	MJ	1,10E+03	9,34E+01	0,00E+00
Renewable, wind, solar, geothe	MJ	1,43E+01	1,14E+01	0,00E+00
Renewable, biomass	MJ	1,06E+02	2,78E+01	0,00E+00
Non-renewable, biomass	MJ	2,21E-02	4,91E-02	0,00E+00
Non-renewable, nuclear	MJ	2,56E+03	7,26E+02	0,00E+00

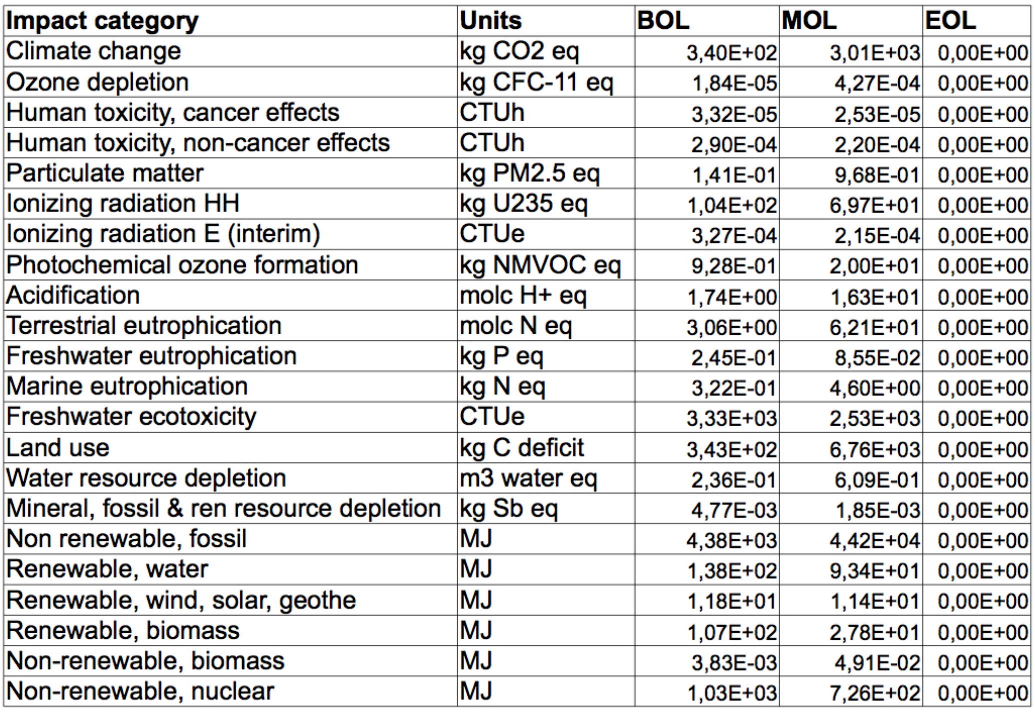
Figure 24: Numerical results for the different life stages for scenario 1.



Impact category	Units	Extrusions	Castings	Sheets	Welding MIG	Welding laser	Transport
Climate change	kg CO2 eq	4,95E+02	3,98E+02	1,64E+03	6,15E+00	9,22E+00	3,41E+01
Ozone depletion	kg CFC-11 eq	1,66E-05	2,35E-05	5,49E-05	2,87E-07	4,31E-07	2,49E-06
Human toxicity, cancer effects	CTUh	1,34E-04	1,11E-04	4,38E-04	1,51E-06	2,27E-06	1,43E-06
Human toxicity, non-cancer effects	CTUh	1,69E-04	2,75E-04	5,40E-04	1,52E-05	2,27E-05	6,42E-06
Particulate matter	kg PM2.5 eq	4,12E-01	2,11E-01	1,37E+00	7,89E-03	1,18E-02	1,22E-02
Ionizing radiation HH	kg U235 eq	3,67E+01	9,61E+01	1,21E+02	7,40E-01	1,11E+00	3,17E+00
Ionizing radiation E (interim)	CTUe	1,09E-04	2,85E-04	3,61E-04	1,56E-06	2,35E-06	1,48E-05
Photochemical ozone formation	kg NMVOC eq	1,51E+00	8,76E-01	5,01E+00	1,91E-02	2,86E-02	1,72E-01
Acidification	molc H+ eq	4,24E+00	2,10E+00	1,41E+01	5,30E-02	7,94E-02	1,47E-01
Terrestrial eutrophication	molc N eq	5,18E+00	2,90E+00	1,72E+01	6,53E-02	9,80E-02	5,26E-01
Freshwater eutrophication	kg P eq	2,84E-01	1,65E-01	9,28E-01	3,61E-03	5,42E-03	3,19E-03
Marine eutrophication	kg N eq	5,32E-01	2,86E-01	1,74E+00	6,65E-03	9,97E-03	4,81E-02
Freshwater ecotoxicity	CTUe	6,56E+03	4,88E+03	2,11E+04	9,31E+01	1,40E+02	2,05E+02
Land use	kg C deficit	3,18E+02	5,79E+02	1,06E+03	3,75E+00	5,63E+00	9,27E+01
Water resource depletion	m3 water eq	3,10E-02	2,23E-01	1,03E-01	6,30E-05	9,45E-05	1,69E-04
Mineral, fossil & ren res.	kg Sb eq	1,63E-02	3,53E-03	8,85E-02	6,86E-05	1,03E-04	1,67E-03
Non renewable, fossil	MJ	4,96E+03	3,96E+03	1,64E+04	6,44E+01	9,67E+01	5,53E+02
Renewable, water	MJ	2,76E+01	9,78E+02	9,20E+01	0,00E+00	0,00E+00	0,00E+00
Renewable, wind, solar, geoth.	MJ	2,60E+00	3,00E+00	8,68E+00	0,00E+00	0,00E+00	0,00E+00
Renewable, biomass	MJ	1,92E+01	2,24E+01	6,40E+01	0,00E+00	0,00E+00	0,00E+00
Non-renewable, biomass	MJ	7,51E-04	1,89E-02	2,50E-03	0,00E+00	0,00E+00	0,00E+00
Non-renewable, nuclear	MJ	3,55E+02	9,99E+02	1,17E+03	8,17E+00	1,23E+01	1,77E+01

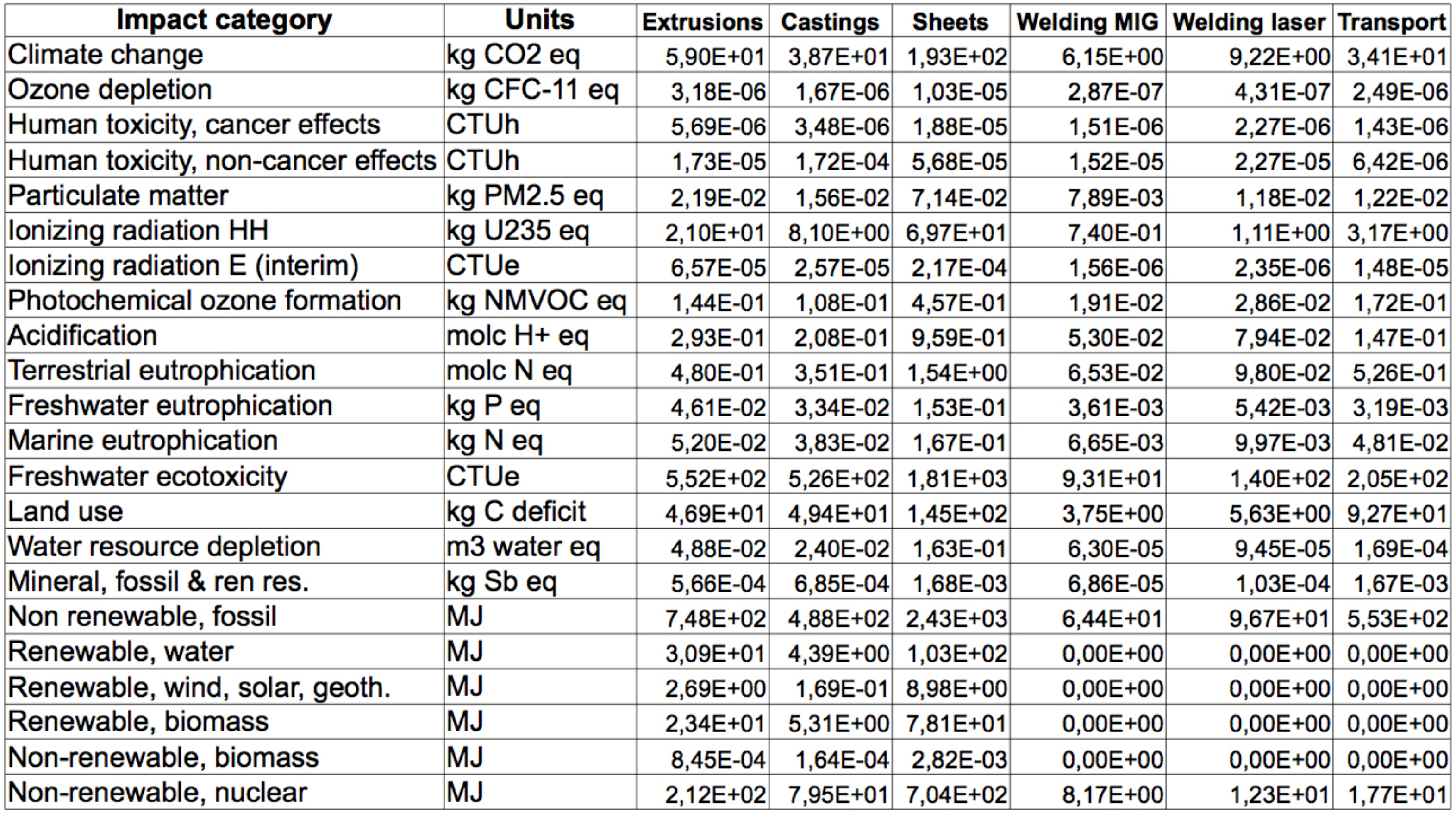
Figure 25: Numerical results for the production for scenario 1.

B.2 Scenario 2: Closed-loop Recycling



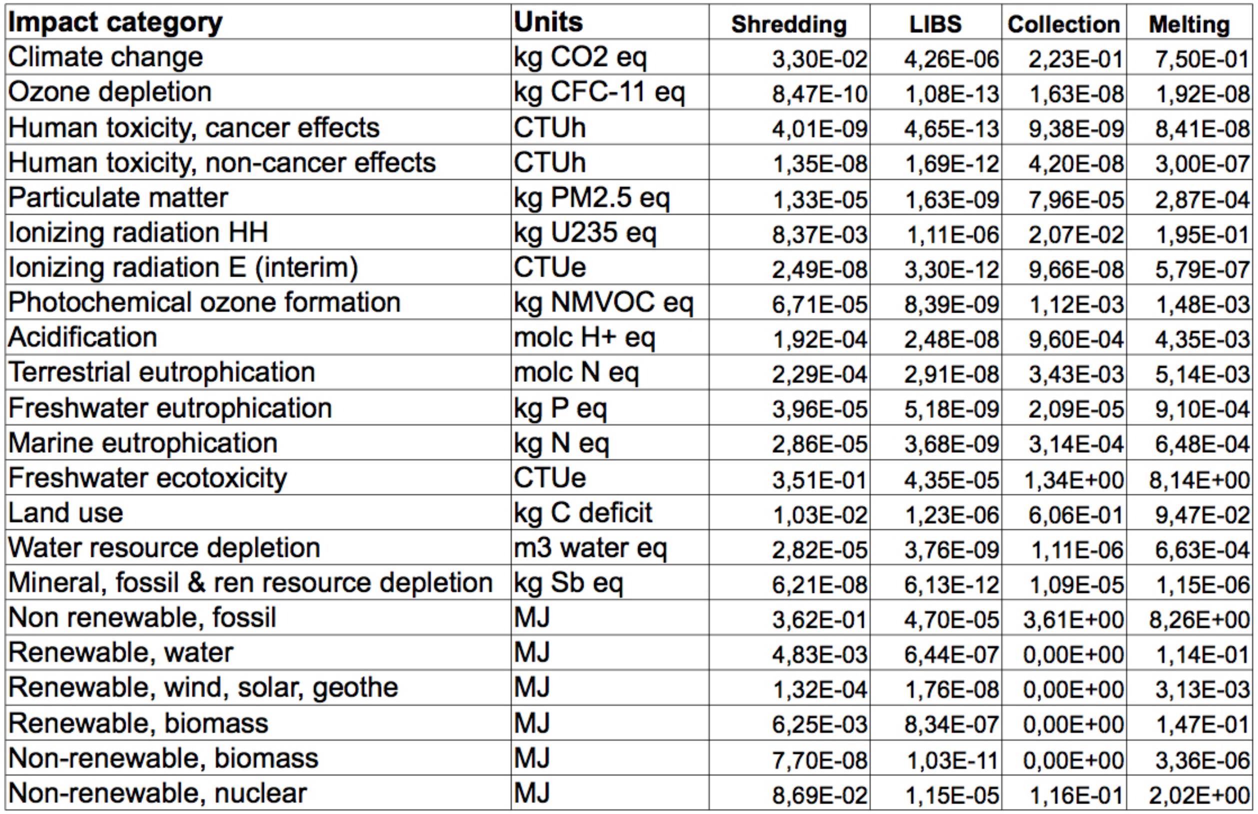
Impact category	Units	BOL	MOL	EOL
Climate change	kg CO2 eq	3,40E+02	3,01E+03	0,00E+00
Ozone depletion	kg CFC-11 eq	1,84E-05	4,27E-04	0,00E+00
Human toxicity, cancer effects	CTUh	3,32E-05	2,53E-05	0,00E+00
Human toxicity, non-cancer effects	CTUh	2,90E-04	2,20E-04	0,00E+00
Particulate matter	kg PM2.5 eq	1,41E-01	9,68E-01	0,00E+00
Ionizing radiation HH	kg U235 eq	1,04E+02	6,97E+01	0,00E+00
Ionizing radiation E (interim)	CTUe	3,27E-04	2,15E-04	0,00E+00
Photochemical ozone formation	kg NMVOC eq	9,28E-01	2,00E+01	0,00E+00
Acidification	molc H+ eq	1,74E+00	1,63E+01	0,00E+00
Terrestrial eutrophication	molc N eq	3,06E+00	6,21E+01	0,00E+00
Freshwater eutrophication	kg P eq	2,45E-01	8,55E-02	0,00E+00
Marine eutrophication	kg N eq	3,22E-01	4,60E+00	0,00E+00
Freshwater ecotoxicity	CTUe	3,33E+03	2,53E+03	0,00E+00
Land use	kg C deficit	3,43E+02	6,76E+03	0,00E+00
Water resource depletion	m3 water eq	2,36E-01	6,09E-01	0,00E+00
Mineral, fossil & ren resource depletion	kg Sb eq	4,77E-03	1,85E-03	0,00E+00
Non renewable, fossil	MJ	4,38E+03	4,42E+04	0,00E+00
Renewable, water	MJ	1,38E+02	9,34E+01	0,00E+00
Renewable, wind, solar, geothe	MJ	1,18E+01	1,14E+01	0,00E+00
Renewable, biomass	MJ	1,07E+02	2,78E+01	0,00E+00
Non-renewable, biomass	MJ	3,83E-03	4,91E-02	0,00E+00
Non-renewable, nuclear	MJ	1,03E+03	7,26E+02	0,00E+00

Figure 26: Numerical results for the different life stages for scenario 2.



Impact category	Units	Extrusions	Castings	Sheets	Welding MIG	Welding laser	Transport
Climate change	kg CO2 eq	5,90E+01	3,87E+01	1,93E+02	6,15E+00	9,22E+00	3,41E+01
Ozone depletion	kg CFC-11 eq	3,18E-06	1,67E-06	1,03E-05	2,87E-07	4,31E-07	2,49E-06
Human toxicity, cancer effects	CTUh	5,69E-06	3,48E-06	1,88E-05	1,51E-06	2,27E-06	1,43E-06
Human toxicity, non-cancer effects	CTUh	1,73E-05	1,72E-04	5,68E-05	1,52E-05	2,27E-05	6,42E-06
Particulate matter	kg PM2.5 eq	2,19E-02	1,56E-02	7,14E-02	7,89E-03	1,18E-02	1,22E-02
Ionizing radiation HH	kg U235 eq	2,10E+01	8,10E+00	6,97E+01	7,40E-01	1,11E+00	3,17E+00
Ionizing radiation E (interim)	CTUe	6,57E-05	2,57E-05	2,17E-04	1,56E-06	2,35E-06	1,48E-05
Photochemical ozone formation	kg NMVOC eq	1,44E-01	1,08E-01	4,57E-01	1,91E-02	2,86E-02	1,72E-01
Acidification	molc H+ eq	2,93E-01	2,08E-01	9,59E-01	5,30E-02	7,94E-02	1,47E-01
Terrestrial eutrophication	molc N eq	4,80E-01	3,51E-01	1,54E+00	6,53E-02	9,80E-02	5,26E-01
Freshwater eutrophication	kg P eq	4,61E-02	3,34E-02	1,53E-01	3,61E-03	5,42E-03	3,19E-03
Marine eutrophication	kg N eq	5,20E-02	3,83E-02	1,67E-01	6,65E-03	9,97E-03	4,81E-02
Freshwater ecotoxicity	CTUe	5,52E+02	5,26E+02	1,81E+03	9,31E+01	1,40E+02	2,05E+02
Land use	kg C deficit	4,69E+01	4,94E+01	1,45E+02	3,75E+00	5,63E+00	9,27E+01
Water resource depletion	m3 water eq	4,88E-02	2,40E-02	1,63E-01	6,30E-05	9,45E-05	1,69E-04
Mineral, fossil & ren res.	kg Sb eq	5,66E-04	6,85E-04	1,68E-03	6,86E-05	1,03E-04	1,67E-03
Non renewable, fossil	MJ	7,48E+02	4,88E+02	2,43E+03	6,44E+01	9,67E+01	5,53E+02
Renewable, water	MJ	3,09E+01	4,39E+00	1,03E+02	0,00E+00	0,00E+00	0,00E+00
Renewable, wind, solar, geoth.	MJ	2,69E+00	1,69E-01	8,98E+00	0,00E+00	0,00E+00	0,00E+00
Renewable, biomass	MJ	2,34E+01	5,31E+00	7,81E+01	0,00E+00	0,00E+00	0,00E+00
Non-renewable, biomass	MJ	8,45E-04	1,64E-04	2,82E-03	0,00E+00	0,00E+00	0,00E+00
Non-renewable, nuclear	MJ	2,12E+02	7,95E+01	7,04E+02	8,17E+00	1,23E+01	1,77E+01

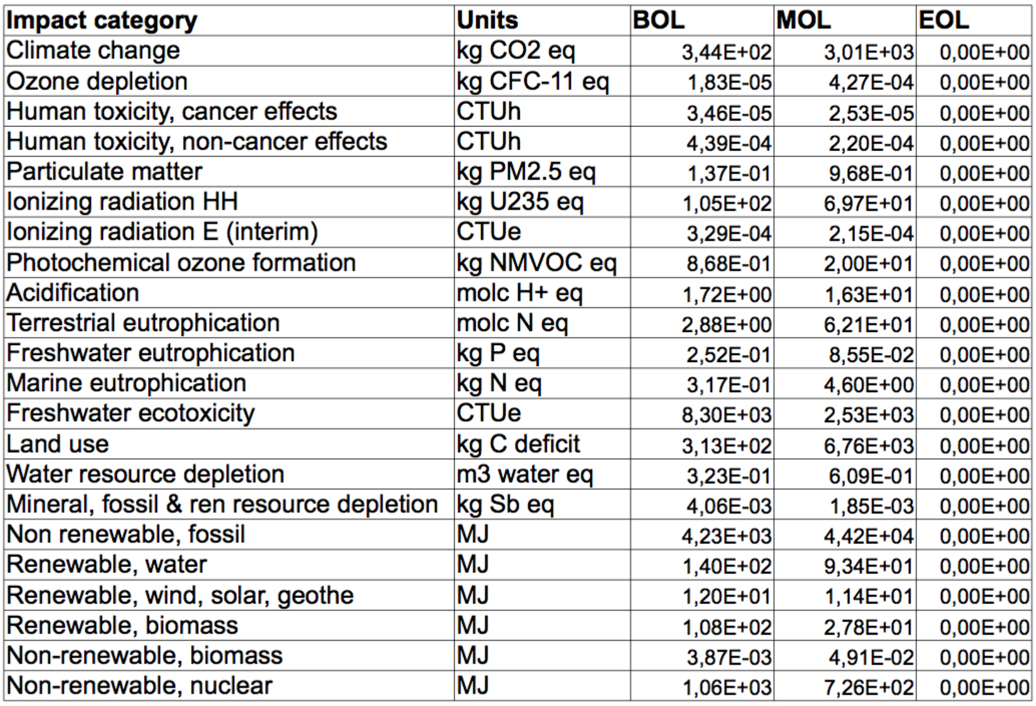
Figure 27: Numerical results for the production for scenario 2.



Impact category	Units	Shredding	LIBS	Collection	Melting
Climate change	kg CO2 eq	3,30E-02	4,26E-06	2,23E-01	7,50E-01
Ozone depletion	kg CFC-11 eq	8,47E-10	1,08E-13	1,63E-08	1,92E-08
Human toxicity, cancer effects	CTUh	4,01E-09	4,65E-13	9,38E-09	8,41E-08
Human toxicity, non-cancer effects	CTUh	1,35E-08	1,69E-12	4,20E-08	3,00E-07
Particulate matter	kg PM2.5 eq	1,33E-05	1,63E-09	7,96E-05	2,87E-04
Ionizing radiation HH	kg U235 eq	8,37E-03	1,11E-06	2,07E-02	1,95E-01
Ionizing radiation E (interim)	CTUe	2,49E-08	3,30E-12	9,66E-08	5,79E-07
Photochemical ozone formation	kg NMVOC eq	6,71E-05	8,39E-09	1,12E-03	1,48E-03
Acidification	molc H+ eq	1,92E-04	2,48E-08	9,60E-04	4,35E-03
Terrestrial eutrophication	molc N eq	2,29E-04	2,91E-08	3,43E-03	5,14E-03
Freshwater eutrophication	kg P eq	3,96E-05	5,18E-09	2,09E-05	9,10E-04
Marine eutrophication	kg N eq	2,86E-05	3,68E-09	3,14E-04	6,48E-04
Freshwater ecotoxicity	CTUe	3,51E-01	4,35E-05	1,34E+00	8,14E+00
Land use	kg C deficit	1,03E-02	1,23E-06	6,06E-01	9,47E-02
Water resource depletion	m3 water eq	2,82E-05	3,76E-09	1,11E-06	6,63E-04
Mineral, fossil & ren resource depletion	kg Sb eq	6,21E-08	6,13E-12	1,09E-05	1,15E-06
Non renewable, fossil	MJ	3,62E-01	4,70E-05	3,61E+00	8,26E+00
Renewable, water	MJ	4,83E-03	6,44E-07	0,00E+00	1,14E-01
Renewable, wind, solar, geothe	MJ	1,32E-04	1,76E-08	0,00E+00	3,13E-03
Renewable, biomass	MJ	6,25E-03	8,34E-07	0,00E+00	1,47E-01
Non-renewable, biomass	MJ	7,70E-08	1,03E-11	0,00E+00	3,36E-06
Non-renewable, nuclear	MJ	8,69E-02	1,15E-05	1,16E-01	2,02E+00

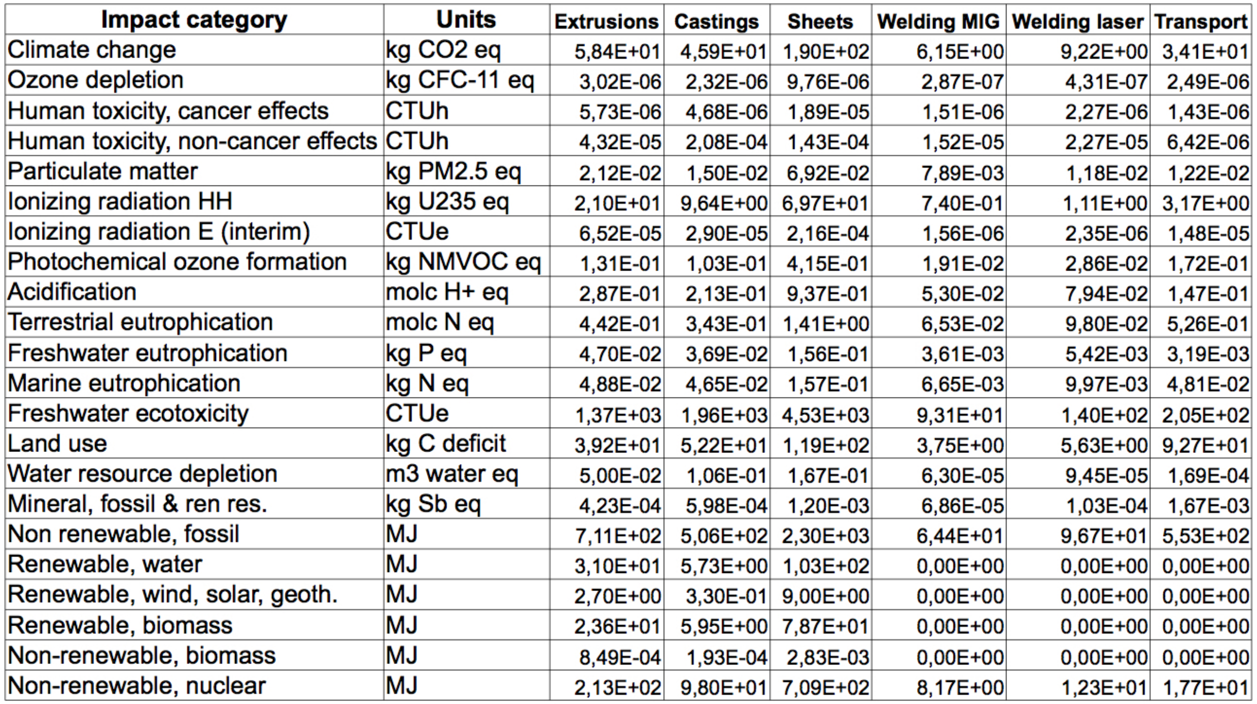
Figure 28: Numerical results for the scrap treatment for scenario 2.

B.3 Scenario 3: Open-loop Recycling



Impact category	Units	BOL	MOL	EOL
Climate change	kg CO2 eq	3,44E+02	3,01E+03	0,00E+00
Ozone depletion	kg CFC-11 eq	1,83E-05	4,27E-04	0,00E+00
Human toxicity, cancer effects	CTUh	3,46E-05	2,53E-05	0,00E+00
Human toxicity, non-cancer effects	CTUh	4,39E-04	2,20E-04	0,00E+00
Particulate matter	kg PM2.5 eq	1,37E-01	9,68E-01	0,00E+00
Ionizing radiation HH	kg U235 eq	1,05E+02	6,97E+01	0,00E+00
Ionizing radiation E (interim)	CTUe	3,29E-04	2,15E-04	0,00E+00
Photochemical ozone formation	kg NMVOC eq	8,68E-01	2,00E+01	0,00E+00
Acidification	molc H+ eq	1,72E+00	1,63E+01	0,00E+00
Terrestrial eutrophication	molc N eq	2,88E+00	6,21E+01	0,00E+00
Freshwater eutrophication	kg P eq	2,52E-01	8,55E-02	0,00E+00
Marine eutrophication	kg N eq	3,17E-01	4,60E+00	0,00E+00
Freshwater ecotoxicity	CTUe	8,30E+03	2,53E+03	0,00E+00
Land use	kg C deficit	3,13E+02	6,76E+03	0,00E+00
Water resource depletion	m3 water eq	3,23E-01	6,09E-01	0,00E+00
Mineral, fossil & ren resource depletion	kg Sb eq	4,06E-03	1,85E-03	0,00E+00
Non renewable, fossil	MJ	4,23E+03	4,42E+04	0,00E+00
Renewable, water	MJ	1,40E+02	9,34E+01	0,00E+00
Renewable, wind, solar, geothe	MJ	1,20E+01	1,14E+01	0,00E+00
Renewable, biomass	MJ	1,08E+02	2,78E+01	0,00E+00
Non-renewable, biomass	MJ	3,87E-03	4,91E-02	0,00E+00
Non-renewable, nuclear	MJ	1,06E+03	7,26E+02	0,00E+00

Figure 29: Numerical results for the different life stages for scenario 3.



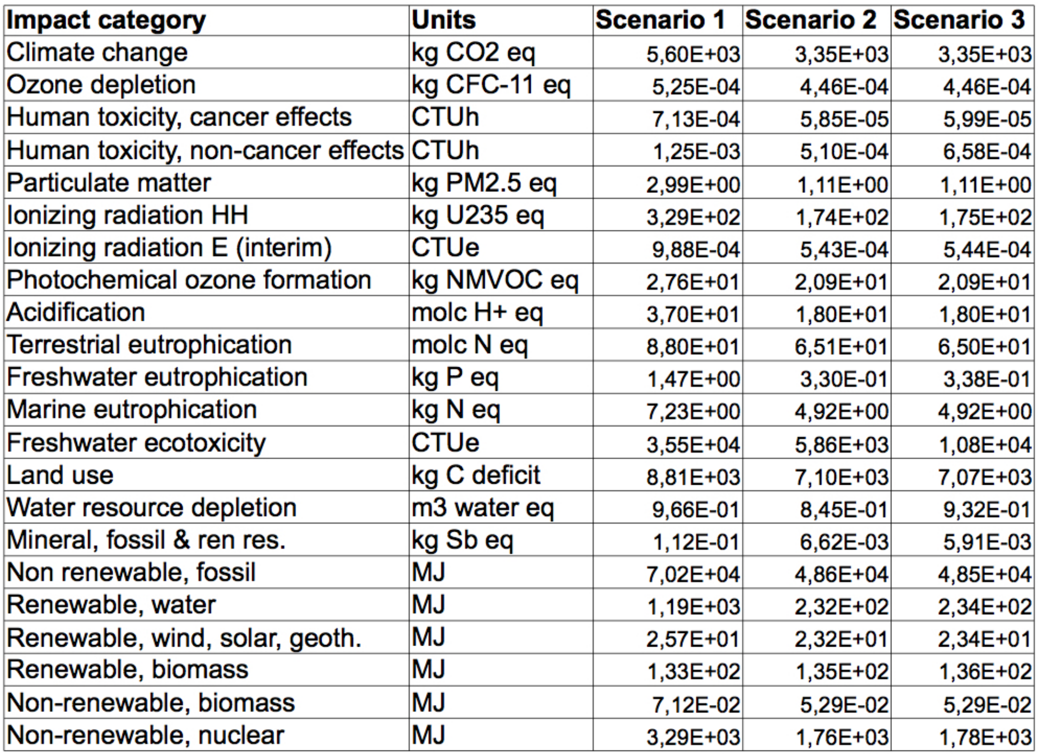
Impact category	Units	Extrusions	Castings	Sheets	Welding MIG	Welding laser	Transport
Climate change	kg CO2 eq	5,84E+01	4,59E+01	1,90E+02	6,15E+00	9,22E+00	3,41E+01
Ozone depletion	kg CFC-11 eq	3,02E-06	2,32E-06	9,76E-06	2,87E-07	4,31E-07	2,49E-06
Human toxicity, cancer effects	CTUh	5,73E-06	4,68E-06	1,89E-05	1,51E-06	2,27E-06	1,43E-06
Human toxicity, non-cancer effects	CTUh	4,32E-05	2,08E-04	1,43E-04	1,52E-05	2,27E-05	6,42E-06
Particulate matter	kg PM2.5 eq	2,12E-02	1,50E-02	6,92E-02	7,89E-03	1,18E-02	1,22E-02
Ionizing radiation HH	kg U235 eq	2,10E+01	9,64E+00	6,97E+01	7,40E-01	1,11E+00	3,17E+00
Ionizing radiation E (interim)	CTUe	6,52E-05	2,90E-05	2,16E-04	1,56E-06	2,35E-06	1,48E-05
Photochemical ozone formation	kg NMVOC eq	1,31E-01	1,03E-01	4,15E-01	1,91E-02	2,86E-02	1,72E-01
Acidification	molc H+ eq	2,87E-01	2,13E-01	9,37E-01	5,30E-02	7,94E-02	1,47E-01
Terrestrial eutrophication	molc N eq	4,42E-01	3,43E-01	1,41E+00	6,53E-02	9,80E-02	5,26E-01
Freshwater eutrophication	kg P eq	4,70E-02	3,69E-02	1,56E-01	3,61E-03	5,42E-03	3,19E-03
Marine eutrophication	kg N eq	4,88E-02	4,65E-02	1,57E-01	6,65E-03	9,97E-03	4,81E-02
Freshwater ecotoxicity	CTUe	1,37E+03	1,96E+03	4,53E+03	9,31E+01	1,40E+02	2,05E+02
Land use	kg C deficit	3,92E+01	5,22E+01	1,19E+02	3,75E+00	5,63E+00	9,27E+01
Water resource depletion	m3 water eq	5,00E-02	1,06E-01	1,67E-01	6,30E-05	9,45E-05	1,69E-04
Mineral, fossil & ren res.	kg Sb eq	4,23E-04	5,98E-04	1,20E-03	6,86E-05	1,03E-04	1,67E-03
Non renewable, fossil	MJ	7,11E+02	5,06E+02	2,30E+03	6,44E+01	9,67E+01	5,53E+02
Renewable, water	MJ	3,10E+01	5,73E+00	1,03E+02	0,00E+00	0,00E+00	0,00E+00
Renewable, wind, solar, geoth.	MJ	2,70E+00	3,30E-01	9,00E+00	0,00E+00	0,00E+00	0,00E+00
Renewable, biomass	MJ	2,36E+01	5,95E+00	7,87E+01	0,00E+00	0,00E+00	0,00E+00
Non-renewable, biomass	MJ	8,49E-04	1,93E-04	2,83E-03	0,00E+00	0,00E+00	0,00E+00
Non-renewable, nuclear	MJ	2,13E+02	9,80E+01	7,09E+02	8,17E+00	1,23E+01	1,77E+01

Figure 30: Numerical results for the production for scenario 3.

Impact category	**Units**	**LIBS**	**Sorting other**	**Collection**	**Melting**
Climate change	kg CO2 eq	4,26E-06	1,22E-01	1,11E-01	7,50E-01
Ozone depletion	kg CFC-11 eq	1,08E-13	3,07E-09	8,14E-09	1,92E-08
Human toxicity, cancer effects	CTUh	4,65E-13	1,03E-08	4,69E-09	8,41E-08
Human toxicity, non-cancer effects	CTUh	1,69E-12	9,76E-07	2,10E-08	3,00E-07
Particulate matter	kg PM2.5 eq	1,63E-09	3,00E-05	3,98E-05	2,87E-04
Ionizing radiation HH	kg U235 eq	1,11E-06	1,87E-02	1,04E-02	1,95E-01
Ionizing radiation E (interim)	CTUe	3,30E-12	5,45E-08	4,83E-08	5,79E-07
Photochemical ozone formation	kg NMVOC eq	8,39E-09	1,63E-04	5,62E-04	1,48E-03
Acidification	molc H+ eq	2,48E-08	4,30E-04	4,80E-04	4,35E-03
Terrestrial eutrophication	molc N eq	2,91E-08	5,61E-04	1,72E-03	5,14E-03
Freshwater eutrophication	kg P eq	5,18E-09	8,33E-05	1,04E-05	9,10E-04
Marine eutrophication	kg N eq	3,68E-09	6,79E-05	1,57E-04	6,48E-04
Freshwater ecotoxicity	CTUe	4,35E-05	3,06E+01	6,70E-01	8,14E+00
Land use	kg C deficit	1,23E-06	3,35E-02	3,03E-01	9,47E-02
Water resource depletion	m3 water eq	3,76E-09	7,40E-05	5,53E-07	6,63E-04
Mineral, fossil & ren resource depletion	kg Sb eq	6,13E-12	3,15E-07	5,45E-06	1,15E-06
Non renewable, fossil	MJ	4,70E-05	8,27E-01	1,81E+00	8,26E+00
Renewable, water	MJ	6,44E-07	1,02E-02	0,00E+00	1,14E-01
Renewable, wind, solar, geothe	MJ	1,76E-08	2,89E-04	0,00E+00	3,13E-03
Renewable, biomass	MJ	8,34E-07	1,31E-02	0,00E+00	1,47E-01
Non-renewable, biomass	MJ	1,03E-11	2,10E-07	0,00E+00	3,36E-06
Non-renewable, nuclear	MJ	1,15E-05	1,95E-01	5,78E-02	2,02E+00

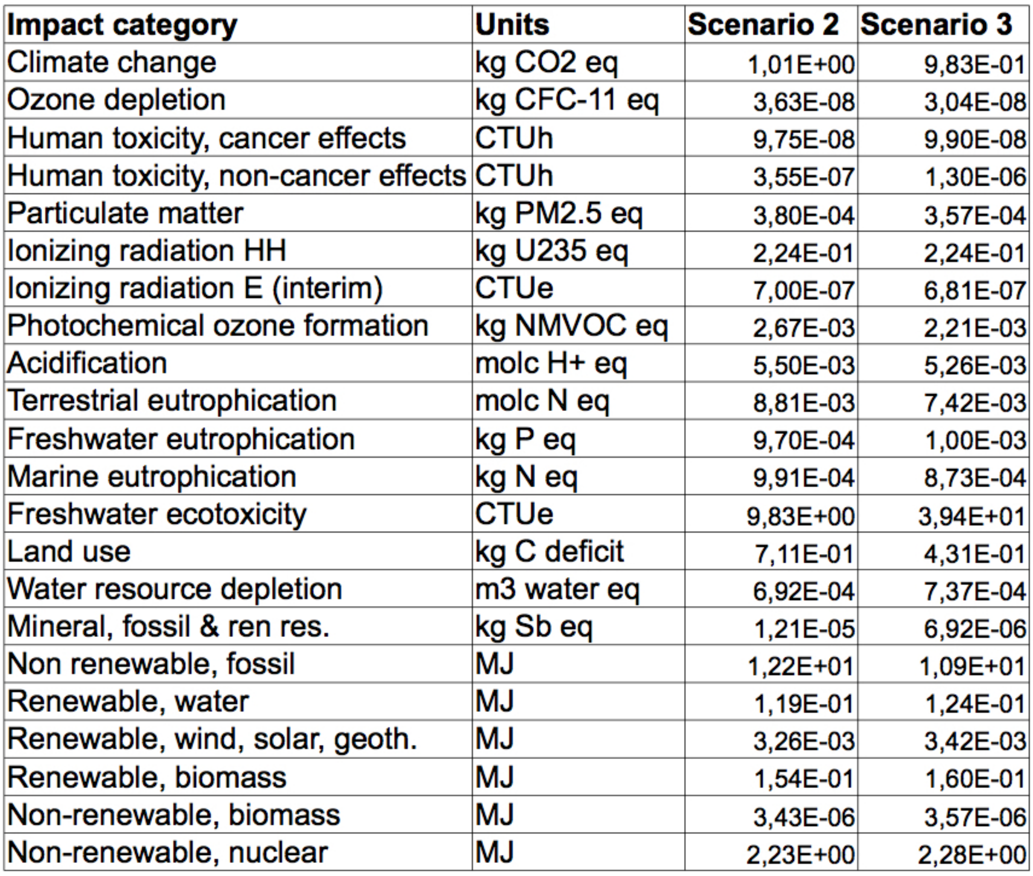
Figure 31: Numerical results for the scrap treatment for scenario 3.

B.4 Comparison



Impact category	Units	Scenario 1	Scenario 2	Scenario 3
Climate change	kg CO2 eq	5,60E+03	3,35E+03	3,35E+03
Ozone depletion	kg CFC-11 eq	5,25E-04	4,46E-04	4,46E-04
Human toxicity, cancer effects	CTUh	7,13E-04	5,85E-05	5,99E-05
Human toxicity, non-cancer effects	CTUh	1,25E-03	5,10E-04	6,58E-04
Particulate matter	kg PM2.5 eq	2,99E+00	1,11E+00	1,11E+00
Ionizing radiation HH	kg U235 eq	3,29E+02	1,74E+02	1,75E+02
Ionizing radiation E (interim)	CTUe	9,88E-04	5,43E-04	5,44E-04
Photochemical ozone formation	kg NMVOC eq	2,76E+01	2,09E+01	2,09E+01
Acidification	molc H+ eq	3,70E+01	1,80E+01	1,80E+01
Terrestrial eutrophication	molc N eq	8,80E+01	6,51E+01	6,50E+01
Freshwater eutrophication	kg P eq	1,47E+00	3,30E-01	3,38E-01
Marine eutrophication	kg N eq	7,23E+00	4,92E+00	4,92E+00
Freshwater ecotoxicity	CTUe	3,55E+04	5,86E+03	1,08E+04
Land use	kg C deficit	8,81E+03	7,10E+03	7,07E+03
Water resource depletion	m3 water eq	9,66E-01	8,45E-01	9,32E-01
Mineral, fossil & ren res.	kg Sb eq	1,12E-01	6,62E-03	5,91E-03
Non renewable, fossil	MJ	7,02E+04	4,86E+04	4,85E+04
Renewable, water	MJ	1,19E+03	2,32E+02	2,34E+02
Renewable, wind, solar, geoth.	MJ	2,57E+01	2,32E+01	2,34E+01
Renewable, biomass	MJ	1,33E+02	1,35E+02	1,36E+02
Non-renewable, biomass	MJ	7,12E-02	5,29E-02	5,29E-02
Non-renewable, nuclear	MJ	3,29E+03	1,76E+03	1,78E+03

Figure 32: Numerical results for all three scenarios.



Impact category	Units	Scenario 2	Scenario 3
Climate change	kg CO2 eq	1,01E+00	9,83E-01
Ozone depletion	kg CFC-11 eq	3,63E-08	3,04E-08
Human toxicity, cancer effects	CTUh	9,75E-08	9,90E-08
Human toxicity, non-cancer effects	CTUh	3,55E-07	1,30E-06
Particulate matter	kg PM2.5 eq	3,80E-04	3,57E-04
Ionizing radiation HH	kg U235 eq	2,24E-01	2,24E-01
Ionizing radiation E (interim)	CTUe	7,00E-07	6,81E-07
Photochemical ozone formation	kg NMVOC eq	2,67E-03	2,21E-03
Acidification	molc H+ eq	5,50E-03	5,26E-03
Terrestrial eutrophication	molc N eq	8,81E-03	7,42E-03
Freshwater eutrophication	kg P eq	9,70E-04	1,00E-03
Marine eutrophication	kg N eq	9,91E-04	8,73E-04
Freshwater ecotoxicity	CTUe	9,83E+00	3,94E+01
Land use	kg C deficit	7,11E-01	4,31E-01
Water resource depletion	m3 water eq	6,92E-04	7,37E-04
Mineral, fossil & ren res.	kg Sb eq	1,21E-05	6,92E-06
Non renewable, fossil	MJ	1,22E+01	1,09E+01
Renewable, water	MJ	1,19E-01	1,24E-01
Renewable, wind, solar, geoth.	MJ	3,26E-03	3,42E-03
Renewable, biomass	MJ	1,54E-01	1,60E-01
Non-renewable, biomass	MJ	3,43E-06	3,57E-06
Non-renewable, nuclear	MJ	2,23E+00	2,28E+00

Figure 33: Comparison of scrap treatment for scenario 2 and 3.