Life cycle assessment of metal alloys for structural applications

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Abstract. The study compared environmental footprints of two types of Al-alloys: well-known 5083 aluminium alloy with magnesium and traces of manganese and chromium in its composition. This material is highly resistant to seawater corrosion and the influence of industrial chemicals. Furthermore, it retains exceptional strength after welding. The comparisons were made to an innovative alloy where the aluminium based matrix is reinforced by metastable quasicrystals (QC), thus avoiding magnesium in its composition. Furthermore, we checked other aluminium ingots' footprints and compared European average and Germany country specific production data. Environmental footprints were assessed via cradle to gate life cycle assessment. Our findings normalized to 1 m^2 plate suggest, that newly proposed alloy could save around 50 % in value of parameters abiotic resources depletion of fossil fuels, acidification, eutrophication, global warming potential and photochemical ozone creation potential if we compare Qc5 to 6 mm 5083 alloy plate. Only abiotic resources depletion of elements and ozone depletion parameters increase for Qc5 compared to 6 mm 5083 alloy plate.

1. Introduction

1.1. The aim of the study

This study has focused on environmental impacts of aluminium alloys known for their high specific strengths and rigidity. Indispensable in a wide variety of applications such as skins of jets and spacecraft fuel tanks, storage tanks, railcars, vehicles, ships and others, Al-alloys are part of aerospace, military and transportation product manufacturing. The study compared two types of Al-alloys: well-known 5083 aluminium alloy with magnesium and traces of manganese and chromium in its composition. This material is highly resistant to seawater corrosion and the influence of industrial chemicals. Furthermore, it retains exceptional strength after welding [1]. The comparisons were made to an innovative alloy where the aluminium based matrix is reinforced by metastable quasicrystalline phases (QC). Quasicrystals have many interesting properties such as high hardness, thermal stability, high corrosion resistance, low coefficient of friction and low interfacial energy [2, 3]. High symmetry and quasiperiodicity contribute to forming the orientation relationship on all the interfaces in the bulk. This leads to important properties such as significant enhancement of strength and ductility of alloys containing quasicrystals [4-6].

1.2. Assumptions made in the study

The study took into account different thicknesses of plates since their characteristics vary in terms of specific strength and rigidity (see Table 1). For comparison, typical 5xxx series alloy 5083-O in soft (annealed) state and Al-alloy reinforced with QC particles Qc5 in the as-cast state were analysed. The 5083-O alloy has the ultimate tensile strength of 290 MPa, tensile yield strength of 140 MPa and elongation at break of 22 % [1], while Qc5 alloy reinforced with QC particles has ultimate compression strength of 610 MPa, compression yield strength of 280 MPa and contraction at break of 32 %. If we assume that the difference between compression and tensile measurement of yield strength is negligible, one can calculate (linear dependence) that alloy reinforced with QC particles will have the same yield strength as 5083-O, when the diameter of the novel alloy is reduced by 50 %. Our observed unit was 1 m^2 panel with similar mechanical characteristics when integrated in applications. However, comparisons were done on 1 kg basis as well, since previous studies presented data in this manner.

Table 1. Plates characteristics.

	5083	**Qc5**
Plate thickness	6 mm	3.9 mm
Density	2.73	3.20
Volume	6000	3900
Plate mass	16.38	12.20

1.3. System boundaries

The modular principle described in the standard EN 15804 has been applied for the system boundaries of this life cycle assessment [8]. The assessment relates to A1 to A3 modules, this is the production phase (from cradle to gate). We have included raw material extraction and processing background data, processing energy data and secondary material input (see **Figure 1**). Transport was not included in the study.

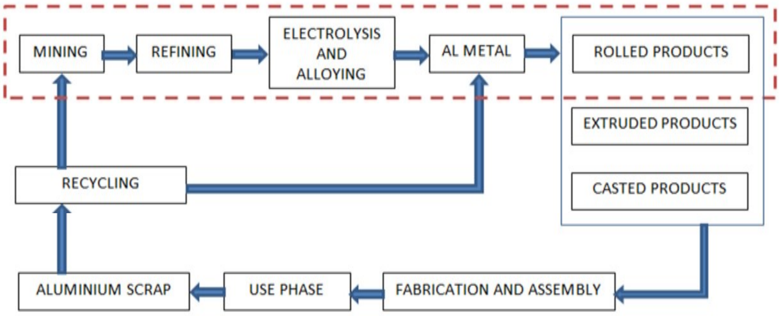

Figure 1. System boundaries.

Life cycle assessment (LCA) followed the rules in ISO 14040 and 14044 (procedure) [7, 9]. Thus principles definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA were applied. Pilot production on a laboratory scale provided limited data, thus some estimates were taken into account.

2. Assessment details

2.1. Production process and materials bill

Novel Al-alloys reinforced with QCs can be classified as aluminium matrix composites (AMCs). AMCs consist of at least two chemically and physically distinct phases that are suitably distributed to provide properties which are not obtained with either of the individual phases. The reinforcing material is usually in the form of the fibres, particles of flakes, while the Al matrix phase is generally continuous and ensures the compliant support. Reinforcing phase, stronger than the matrix, is embedded in the matrix in discontinues way [10]. In our case, a matrix is aluminium based and the reinforcement phase is a metastable QC phase. The production process is thus majorly simplified by the fact, that reinforcing QC phase grow from within the matrix during the solidification of the melt. The investigated aluminium alloy sheets were cast to a thickness ranging between 3.9 and 7 mm by twin-roll strip casting technology. Cold rolling the strips to an intermediate gauge and reroll annealing the intermediate gauge material is then applied. The reroll-annealed material is then cold rolled to a final sheet gauge followed by a final recrystallizing or back annealing. The combination of controlled casting parameters, controlled amounts of iron, silicon, manganese (Mn), chromium and magnesium (Mg) and reroll and final annealing temperatures results in an improved sheet product in terms of finer grain size, higher elongation and formability, age softening and better corrosion resistance.

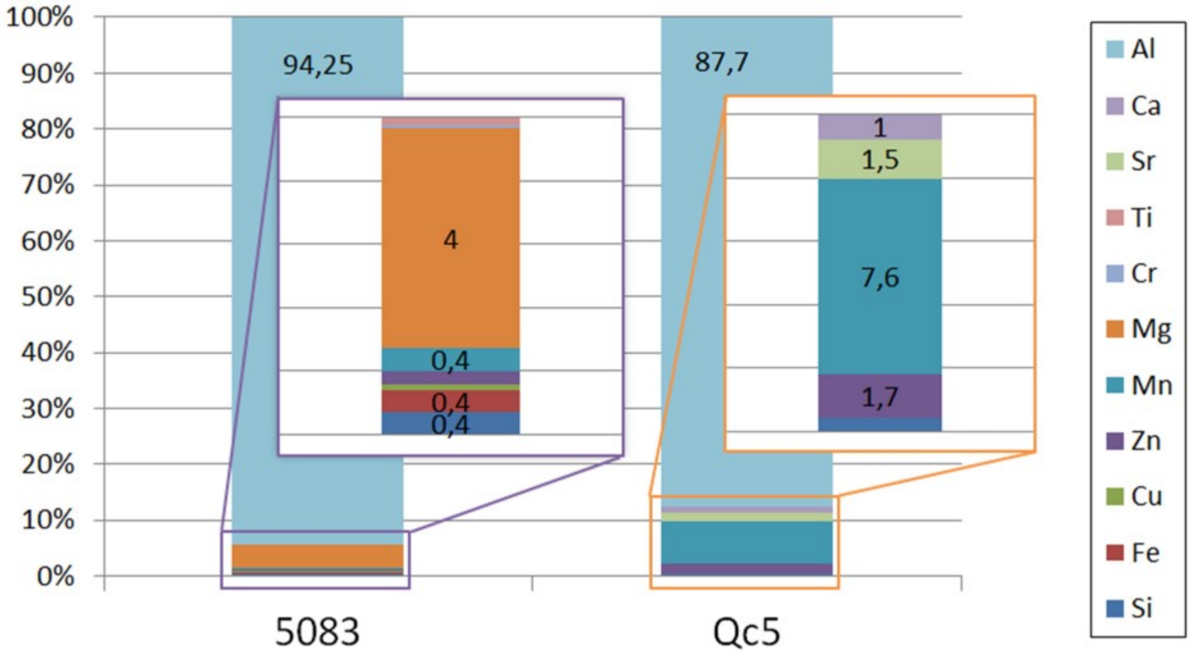

Figure 2. Materials composition (%) for 5083 alloy (left) and Qc5 alloy (right).

2.2. Impact assessment

We have analysed environmental impacts for the production phase of rolled products (see Figure 2). The boundaries were thus set a bit differently than in some other studies, where recycling has also been assessed, for example in a life cycle assessment report published by Aluminum Association [11]. The focus of our research was mainly to compare different compositions of alloys. The results were calculated according to the standard EN 15804, chapter 7.2.2 [8]. The impact assessment was carried out for the impact categories using CML 2001 characterisation factors. We will report and compare the following parameters in this presentation: Global warming potential [kg CO_2-Equiv.], Ozone depletion potential [kg R11-Equiv.]; Acidification of land and water potential [kg SO_2-Equiv.]; Eutrophication potential [kg Phosphate-Equiv.]; Photochemical ozone creation potential [kg Ethene-Equiv.]; Depletion of abiotic resources potential (elements) [kg Sb-Equiv.] and Depletion of abiotic resources potential (fossil) [MJ]. The calculations were done in Gabi software (Thinkstep).

Global warming potential (GWP_{100}) is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide. A GWP is calculated over a specific time interval (100 years). GWP is expressed as a factor of carbon dioxide (whose GWP is standardized to 1). **Acidification Potential (AP)** caused by pollutants SO_2, NO_x, NH_x affect the soil, groundwater, surface water, biological organisms, ecosystems and materials (buildings), which is one of the consequences of crumbling building materials and accelerated corrosion of surfaces. **Eutrophication Potential (EP)** measures the increase of excess nutrients in the water (especially nitrogen and phosphorus). Excess nutrients alter the balance of species in aquatic and terrestrial ecosystems. Large concentrations of excess nutrients can also seriously affect drinkability of surface waters. **Ozone Depletion Potential (ODP)** as a result of anthropogenic emissions. Thinning of the ozone in the stratosphere increases the proportion of UVB radiation that reaches the Earth's surface. UVB radiation relates to human and animal health, the balance of aquatic and terrestrial ecosystems, biochemical cycles and materials. **Photochemical ozone creation potential (POCP)** - the formation of ozone in the troposphere (bordering the Earth's surface) is caused by oxides of nitrogen (NO_x) and volatile organic compounds (VOC). Ozone in the troposphere causes damage to the materials (accelerated oxidation), plants (crop injury) and has adverse effects on humans (eg. Asthma). **Abiotic Resources Depletion Potential** - fossil fuels and other sources are evaluated separately.

2.3. Estimations and background check

We have found previous studies and data of other aluminium alloys A1-A3 environmental footprints and compared them. All comparisons in this chapter were normalized to 1 kg of material. First, we have checked country specifics and found out the aluminium ingot mix footprint for Germany, for example, causes roughly 9 kg CO_2-Equiv in terms of global warming potential, but EU average is a bit lower, 8.3 CO_2-Equiv. This is probably due to country-specific production energy background environmental data, since the material composition for those two cases is the same.

Then, we have found and compared environmental data for aluminium sheets of different material composition: $AlCu_4Mg$, $AlMg_3Mn$ and $AlMg_3$ all with the Germany country-specific data. Furthermore, a very interesting study by Nuss and Eckelman presented a Periodic table of global warming potentials (GWPs) and the data we took into account are consistent with the results of the mentioned study [12].

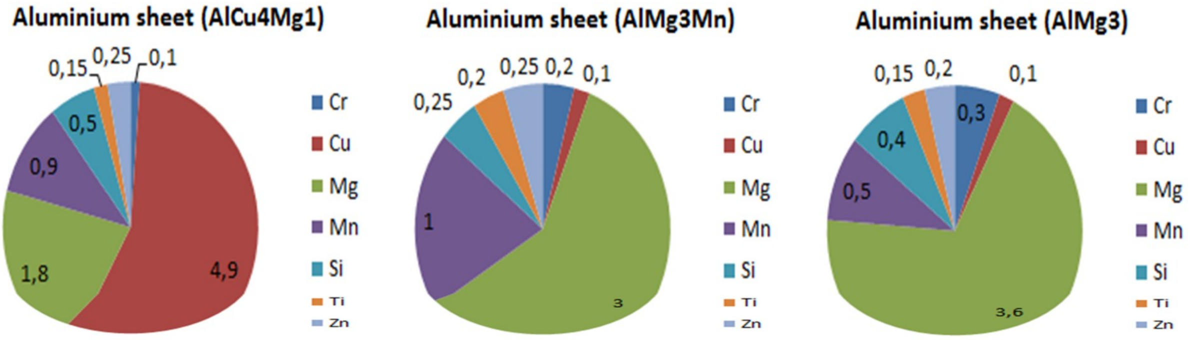

Figure 3. Materials composition of alloys.

Our conclusion was that material composition is an important factor as is energy and auxiliary materials used in production.

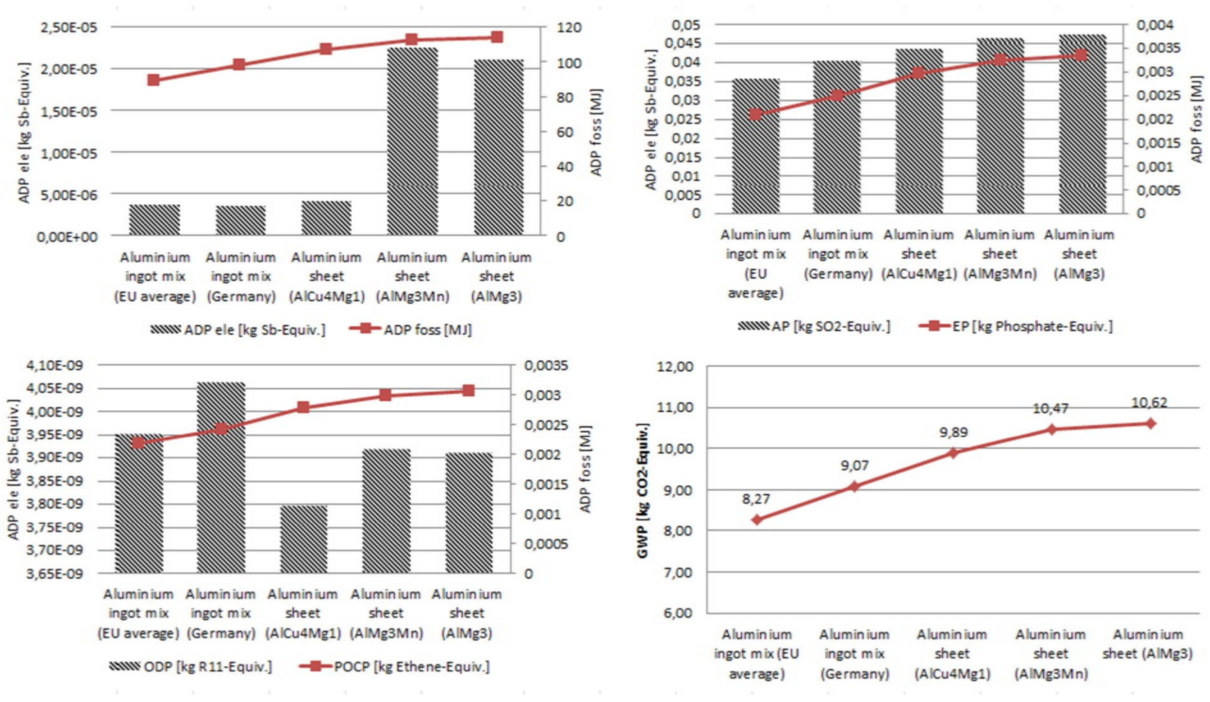

Figure 4. Results of previous studies: different alloys and comparison between European average and German country-specific data.

3. Results

3.1. Innovative Qc5 material calculation rules, datasets and system background

Cut-off rules took into account the fact, that only pilot laboratory production data is available at the moment for innovative metal alloy. LCA analysis included all input data regarding materials and their specifics. Basic raw material and auxiliary materials (water) were modelled by datasets provided in by Thinkstep and Ecoinvent. Consisting of various processes in which the production or recovery of multiple metals occurs simultaneously, the metals production system is highly interconnected. For the innovative alloy production, dataset for Slovenian electricity mix has been applied in the model. Process energy has been summed up and imitated by dataset “Thermal energy from natural gas” (thus a safety factor has been taken into account). Compared alloys differ in materials composition, 5083 alloy consists of 94 % of aluminium, on the other hand, aluminium represents only around 88 % of the total mass in the innovative Qc5 alloy. 7.6 % manganese is added to Qc5 alloy and no magnesium. But in 5083 there is 4 % of magnesium and only 0.4 % of manganese. Thus, we have expected the significantly lower environmental impact in terms of materials composition.

3.2. Results and interpretation

Results were calculated per 1 kg of alloy and for 1 m^2 of the plate so we were able to compare them to alloys investigated in the previous studies.

Table 2. Results for compared alloys (5083 and innovative Qc5).

		per 1 kg	**per 1 kg**	**per 1 m^2**	**per 1 m^2**
ALLOY		**5083**	**Qc5**	**5083**	**Qc5**
ADP ele	[kg Sb-Equiv.]	1,07E-05	2,46E-05	1,74E-04	3,00E-04
ADP foss	[MJ]	9,89E+01	9,08E+01	1,62E+03	1,11E+03
AP	[kg SO2-Equiv.]	4,23E-02	4,38E-02	6,93E-01	5,35E-01
EP	[kg Phosphate-Equiv.]	2,91E-03	2,50E-03	4,77E-02	3,05E-02
GWP	[kg CO2-Equiv.]	9,37E+00	8,45E+00	1,53E+02	1,03E+02
ODP	[kg R11-Equiv.]	4,58E-09	8,96E-09	7,50E-08	1,09E-07
POCP	[kg Ethene-Equiv.]	2,74E-03	2,54E-03	4,49E-02	3,10E-02

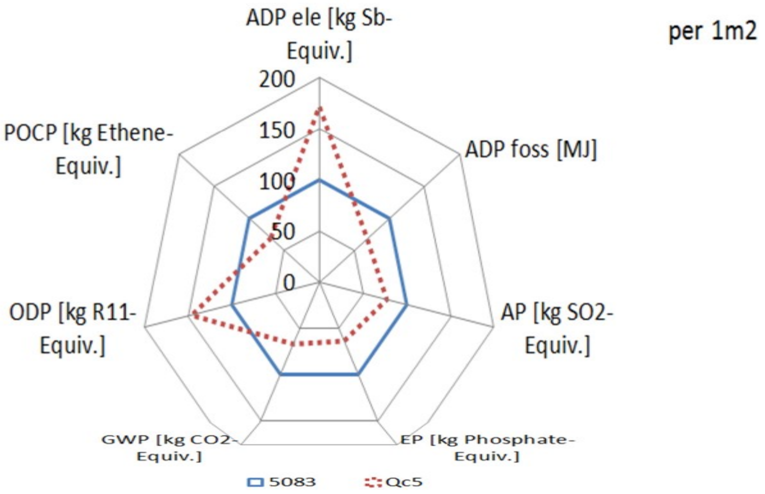

Figure 5. Comparison of the results for 1 m^2 plates of 5083 alloy and innovative Qc5 alloy in % of multiple environmental footprint potential parameters.

Our general finding include are that the innovative alloy Qc5 has significantly smaller environmental footprints in terms of global warming potential, eutrophication potential, acidification potential, fossil abiotic depletion potential and photochemical ozone creation potential per 1 m^2 plate compared to 5083 alloy. However, ozone depletion potential and elements abiotic depletion potential are higher than the footprints of 5083 alloy 1 m^2 plate. Results revealed 33 % lower global warming potential, 33 % lower eutrophication potential, 23 % lower acidification potential, 32 % lower fossil abiotic depletion potential and 31 % lower photochemical ozone creation potential per 1 m^2 plate compared to 5083 alloy.

Compared to previously done studies where environmental footprints were calculated for aluminium ingot mix (European average production and German production) as well as aluminium sheets production of specific compositions: $AlCu_4Mg$, $AlMg_3Mn$ and $AlMg_3$, we can see that innovative Qc5 alloy showed promising results in terms of fossil abiotic depletion potential, eutrophication potential, acidification potential, photochemical ozone creation potential and global warming potential (see Figure 6).

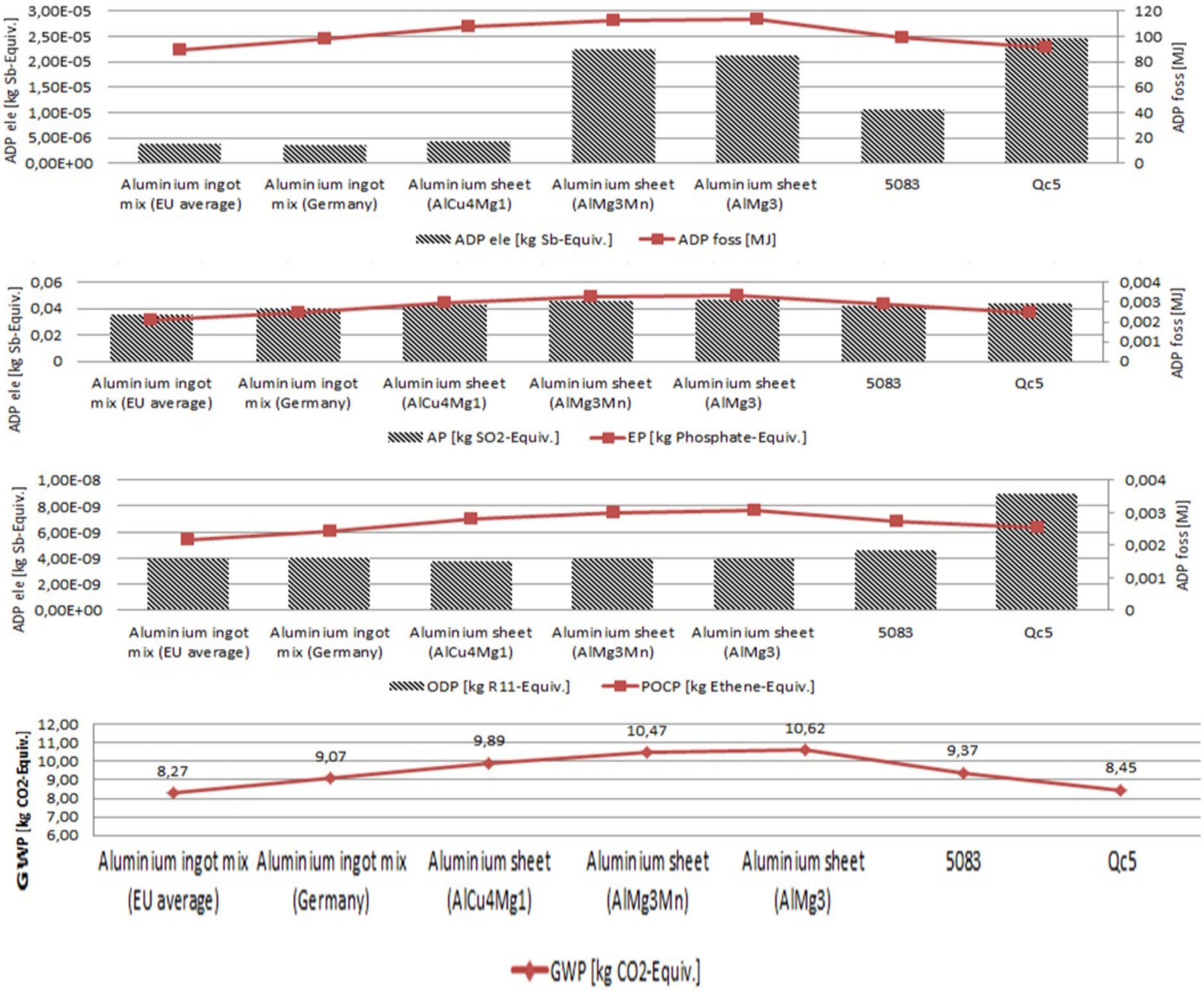

Figure 6. Comparison of environmental footprints for aluminium ingot mix (European average production and German production), sheets production of specific compositions: $AlCu_4Mg$, $AlMg_3Mn$ and $AlMg_3$, 5083 alloy and innovative Qc5 alloy.

A closer look into specific contributors of different environmental footprint parameters is revealed in Figure 7. In terms of GWP, ADP fossile, AP, EP and POCP potentials, aluminium ingot is the biggest contributor by far. Since this is the biggest part also in terms of product mass balance (88 %), the result has been expected. In Qc5 manganese that represents 7.6 % of the mass is the second biggest contributor for those same parameters. ADP elements parameter is mainly influenced by zinc and ODP is caused by zinc and aluminium ingot almost by the equal rate for Qc5 alloy. In 5083 alloy visible contributor in ADP fossile, AP, EP, GWP and POCP is magnesium. Copper plays a major role besides zinc and aluminium ingot for ADO elements.

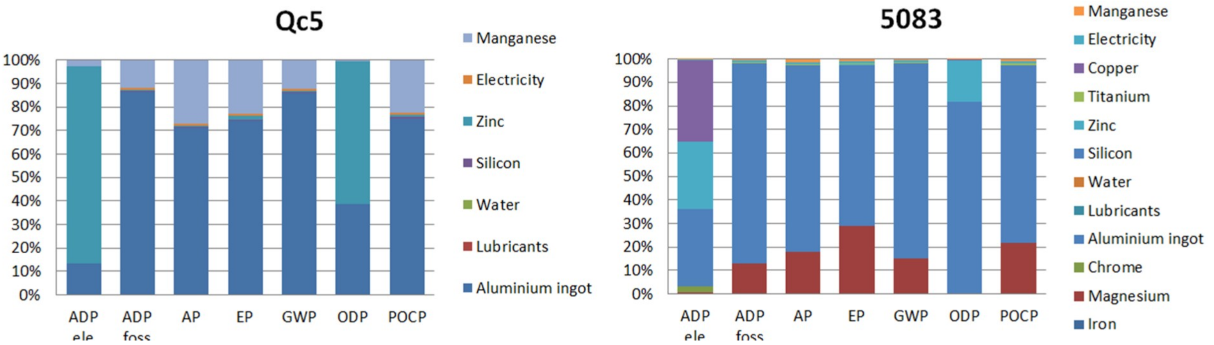

Figure 7. Specific contributors of different environmental footprint parameters for 5083 and Qc5 alloys.

4. Conclusion

An innovative Qc5 alloy was compared to other alloys in terms of environmental footprints related to the production. The study was done according to the standards ISO 14040 and ISO 14044. From cradle to gate (A1-A3 modules) of product's life cycle were studied only. LCA analysis included all input data, such as the basic raw material/materials, auxiliary materials (water) and energy in the production process provided by the producer. Process energy, water and electricity allocation has been provided by researchers proposing an innovative Qc5 alloy and was estimated based on the pilot production of 5083 alloy plates. Qc5 alloy has significantly smaller environmental footprints in terms of global warming potential, eutrophication potential, acidification potential, fossil abiotic depletion potential and photochemical ozone creation potential per 1 m^2 plate compared to 5083 alloy. Compared to previously done studies where environmental footprints were calculated for aluminium ingot mix (European average production and German production) as well as aluminium sheets production of specific compositions: $AlCu_4Mg$, $AlMg_3Mn$ and $AlMg_3$, we can conclude that innovative Qc5 alloy showed promising results in terms of fossil abiotic depletion potential, eutrophication potential, acidification potential, photochemical ozone creation potential and global warming potential.

5. References

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