LCA of a carbon fibre wrapped pressure vessel for automotive applications

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ABSTRACT

While hydrogen technologies are rapidly taking advantage of the research results of the last years, some more effort is necessary to evaluate the impacts that such technologies have on the environment and on the use of existing energy resources compared to conventional technologies. In automotive applications, e.g., the adoption of fuel cell as power generator surely abates emissions during operation but still required an accurate evaluation of impacts during its production process. As a logical follow-up to that analysis, a preliminary LCA study about pressure vessels for hydrogen storage in vehicles was performed. The main scope of the study was the definition of parameters suitable for a comparison between gasoline/diesel tanks and hydrogen tanks for automotive applications.

The vessels are made of aluminium and externally reinforced with a carbon fibre wrapping. The carbon fibre production process was particularly analysed in order to acquire reliable inventory data for the analysis.

FRAMEWORK

Automotive applications of the hydrogen technology are spreading over the world with several examples of fuel cells and ICE propelled cars presented by the most important car manufacturers. A key point of hydrogen applicability to the mobile environment is the possibility of storing the proper quantities of hydrogen onboard to assure an endurance comparable to that of conventional cars. High pressure storage devices together with cryogenic vessels represent the best solutions for this issue. In this paper, the high pressure composite material tank is examined under the environmental impact of its production process point of view, with the adoption of a Life Cycle Assessment methodology.

OBJECTIVE

The purpose of this study is to quantify energy and resources consumption and emission of pollutant to the environment resulting from a preliminary ecoprofile of a tank system to store high pressure hydrogen according to the system boundary definition.

System boundary

Table 1 shows the existing classification of pressure tanks according to their composition. The present study analysed a Type III cylinder.

The functional unit of the study is defined as the production of a high pressure hydrogen composite tank – type III.

The boundaries of the considered industrial system include all the phases from raw materials extraction to the production of a hydrogen composite tank. In detail, the system comprehends:

- raw materials extraction and treatments for the materials used in the production of the tank;
- production and distribution of the energy used in the processes;
- transports involved by the system from raw materials extraction to the final production;
- materials production;
- tank production.

The considered system does not include the assembling phase on the car and end of life of the tank.

Table 1. Cylinders types

Type	Description
I	all steel or aluminium tanks
II	steel or aluminium cylinders reinforced with filament wrapping
III	metal liner reinforced with filament wrapping
IV	cylinders with non-metallic liners (such as plastic) with resin impregnated filament wrappings

INVENTORY ANALYSIS

A high pressure hydrogen composite tank is constituted by a seamless, one piece, permeation resistant, cross-linked, aluminium liner that is over wrapped with multiple layers of carbon fiber/epoxy resin (Type III). The internal volume of the considered tank is 43 litres with an outside diameter of 14 cm and a total outside length of 100 cm.

A schematic view of the tank is shown in Figure 1 while materials of the vessel are reported in Table 2.

Table 3 shows the weight composition of the sample tank.

Figure 1. High pressure cylinder – Type III [courtesy of Dynetek Industries Ltd.]

Table 2. Materials of the tank components

Component	Material	Origin	Main shaping treatments	Material form
liner	Aluminium alloy	Secondary	Cold rolling – cutting	Shaped sheet
Filament material	Carbon fibre	Synthetic	-	filament
Resin	Epoxy resin	Synthetic	-	liquid

Table 3. Tank composition by weight [kg]

Component	Material	Weight
liner	Aluminium alloy	9
Filament material	Carbon fibre	7.5
Resin	Epoxy resin	5
Total		21.5

Methods and data sources

For some of the cited materials, primary LCA data are not available due to lack of information and their confidentiality. To conclude the analysis it was therefore necessary to use secondary data or, in few cases, to adopt alternative and opportune materials for which LCA data were available. These alternative materials have been selected on the basis of the necessary characteristics and performances.

Liner – The liner must be a seamless cylinder made of aluminium alloy 6061 (T-6 temper). The production process of the liner comprehends cold or hot backward extrusion, cold drawing or extrusion of the tube with swaged or spun ends. Special attention is devoted to the neck region where no fold, due to the forming or spinning process, must be sharp or deep or detrimental to the integrity of the cylinder.

Additional work is done onto the inner surface in order to avoid defects which may be removed by machining or other method, provided the metal loss is minimal and the minimum required wall thickness is maintained. Liner ends must be concave to pressure.

For this analysis, the Al 5182 alloy was considered for the secondary aluminium, while the Al 5082 alloy was assessed ad primary aluminium because these are the most similar to the real ones adopted for the tank production, under the chemical composition point of view. Data on these alloys were available from the database adopted. Description of both alloys is comprehensive of cold rolling process.

Filament materials: carbon fiber - Carbon fibres utilised in the considered tank are polyacrylonitrile (PAN) based carbon fiber tows (commercial name: TORAY™ T700 12k).

This material was not available in the adopted LCA database and primary data on this particular material are often very difficult to obtain from producers due to confidentiality reasons. For the analysis, the material was thus substituted with acrylonitrile fibre as this can be considered as the precursor of the fibre and the effect of the exclusion, at this stage of the analysis, of the carbonisation process, is negligible.

Resin matrix materials - Resin matrix systems must be epoxy or modified epoxy type having a pot life compatible with the filament winding process used. The resin matrix system selected must have sufficient ductility so that cracking of the resin matrix system does not occur during the manufacturing of the cylinder or during normal operation for the useful life of the cylinder. The considered tank utilises a liquid resin whose commercial name is EPON™ resin 826/EPI-CURE™ Curing Agent 9551. In the present study an equivalent liquid resin was considered, which characteristics are comparable to those of the commercial product.

Tank production: the realisation of a vessel of this kind requires several operations, the most important of which are: forging of the liner, filament winding and polymerisation. In the present analysis. Only the energy consumption due to polymerisation in a methane fuelled oven was considered, as all interviewed companies

It is important to underline the importance of the technology used to produce a material and the country where the production sequence takes place.
In the case of metals, for instance, it is important to know if the process refers to a primary or secondary material. In this study, two scenarios where analysed:

1- the aluminium alloy contains only primary aluminium
2- the aluminium alloy contains only secondary aluminium

Table 4. Fuels used for electricity production.

Fuel type	*Italy*	*Europe*
Coal	10.8%	22.3%
Oil	46.2%	8.7%
Gas	21.8%	12.1%
Hydro	9.2%	6.1%
Nuclear	10.4%	40.2%
Lignite	0.4%	8.8%
Biomass	0.2%	0.8%
Unspecified	0.4%	0.7%
Peat	-	0.3%
Geothermal	0.5%	-
Solar	-	-
Total	**100%**	**100%**

About energy mix, at this stage only one energy scenario is considered as if the production process of the vessel took place in Italy, thus the Italian energy mix is considered (Table 4) for the work done on aluminium .
Table 5 shows which energy mix was chosen for each material involved in the analysis and the secondary data source. It is to be underlined that energy consumption due to production and work done on epoxy resin and carbon fibre is charged on the European energy mix.

Table 5. Scenarios and databases adopted for the analysis.

Material	*Scenario*	*Energy mix*	*Data base*
Aluminium	Primary	Italy	Boustead v. 4.4
Aluminium	Secondary	Italy	Boustead v. 4.4
Epoxy resin	-	Europe	APME
Carbon Fibre	-	Europe	APME

Life Cycle Inventory results

The analysis performed lead to the following results shown in Figure 2 and 3. The gross energy requirement figure is shown for both scenarios: primary and secondary aluminium. Figure 3 shows the fuel type constitution of the Ger in the secondary aluminium case.

Figure 2. Gross energy requirement [MJ/tank]

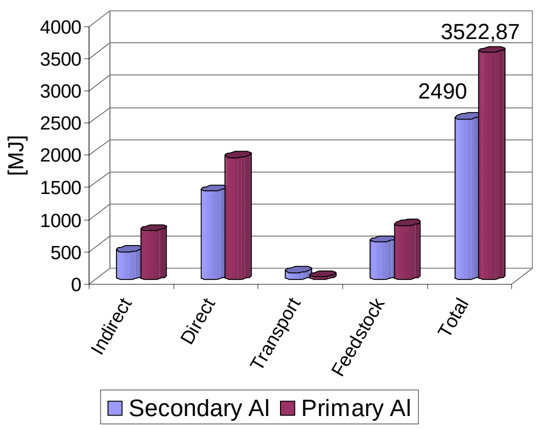
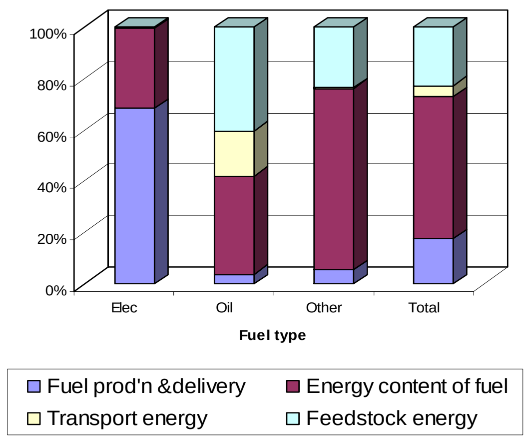


Figure 3. Fuel type analysis of the GER (secondary Al)



In Table 6 other raw materials associated with the vessels materials production and process are shown (materials with a contribution under 500 mg are omitted).

Table 6. Other raw material inputs [mg]

Material	*Secondary Al*	*Primary Al*
Mg	670.904	402.167
N2	1.482.675	1.468.746
O2	3.241.946	246.027
Air	7.039.427	10.942.498
Aluminium scrap	13.668.544	0
Bauxite	50.326	34.811.114
Fluorspar	825	631.880
Limestone (CaCO3)	6.280.935	5.202.505
Sodium chloride (NaCl)	9.844.358	9.698.589
Other	< 500	< 500

Figure 4 and 5 show the different contribution to the GER in case of the use of primary and secondary aluminium.

Figure 4. Contribution to GER (secondary Al)

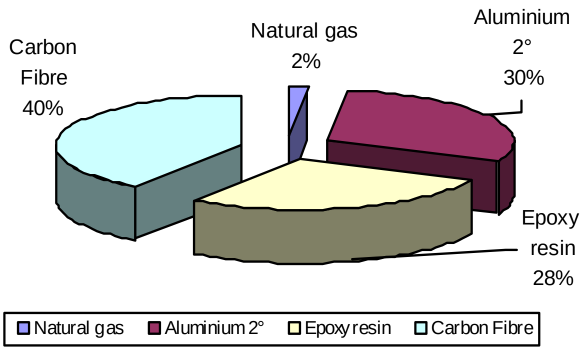
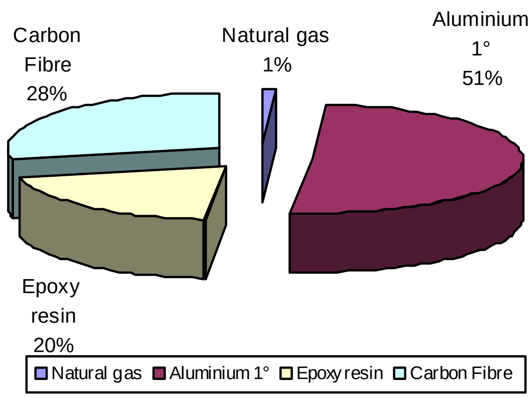


Figure 5. Contribution to GER (primary Al)



LIFE CYCLE IMPACT ASSESSMENT

Table 7 shows results of the life cycle impact assessment: it ca be seen that the adoption of primary or secondary aluminium only affects the global warming potential and the acidification figures, while the others remain quite constant.

Table 7. LC impact assessment results

Impact category	*Secondary Al*	*Primary Al*
GWP100 mg CO2	126.399.843	150.590.669
EP mg O2	94.347.541	94.326.772
AP mmol H+	40.601	53.241
POCP mg C2H4	112.493	115.031
ODP mg CFC11	104	104
Total water use mg	3.797.208.111	3.856.229.280

INTERPRETATION AND CONCLUSIONS

From the analysis and from Figure 4 and 5, it can be noticed that the contribution of the materials production to the GER is generally more important than that of the work done on them. The contribution to the GER in terms of natural gas is mainly due to the oven where polymerisation occurs. For this reason no other energy mixes were analysed, as the data available on e.g. aluminium production are independent of the country mix.

As a next step it could be interesting to obtain detailed data on carbon fibre production from companies in order to refine obtained results.

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