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Role of hydrogen tanks in the life cycle assessment of fuel cell-based auxiliary power units

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HIGHLIGHTS

- Environmental and costs analysis of FC-based APUs.
- Environmental performances of Solid-State H2 storage similar to pressure tanks.
- Gas compression crucial for storage systems.
- The use of structural materials should be reduced.

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ABSTRACT

In the framework of the European project SSH2S, a solid-state hydrogen storage tank - fuel cell system was demonstrated as Auxiliary Power Unit (APU) for a light duty vehicle. In this work, we have assessed the environmental impacts and the costs of the system developed. Following an eco-design approach, we have identified the processes mostly contributing to them and we have suggested possible improvements. By performing a Life Cycle Assessment (LCA), we found that, when the electricity consumption for hydrogen gas compression is included into the analysis, a solid-state hydrogen storage tank has similar greenhouse gas emissions and primary energy demand than those of type III and IV tanks. However, the resources depletion is higher for the solid-state system, even though the inclusions of the end of life of the APU and the recycling of the materials may result in different conclusions. The costs of an APU equipped with a solid-state hydrogen storage tank are significantly higher, about 1.5–2 times the systems based on type III and IV tanks. However, mature technologies are compared with a prototype, which has much room for optimization. To improve both the environmental and economic performances of the APU, a reduction of structural materials for both the solid-state hydrogen tank and Balance of Plant is recommended.

1. Introduction

The European Union has set ambitious climate and energy targets for 2020 in its climate and energy package [1]. These targets, known as the “20-20-20” targets, set three key objectives for 2020: (i) a 20% reduction in EU greenhouse gas emissions from 1990 levels; (ii) raising the share of EU energy consumption produced from renewable resources to 20%; (iii) a 20% improvement in the EU's energy efficiency. These targets are considered a first step towards building a low-carbon economy.

In this climate and energy framework, heavy duty transport plays a critical role, as it is one of the most difficult to be decoupled from the use of fossil fuels. Moreover, the main Internal Combustion Engine (ICE) of the truck is used not only for traction, but also for electricity

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production to power the truck when it is not travelling. Due to the low efficiency of this power generation method, and to the increased number of regulations limiting the idling of the main engine, the separation the two functions, i.e. traction and power supply, is becoming attractive in order to reduce emissions of noise and pollutants [2].

Auxiliary Power Units (APUs) are considered one of the promising applications of fuel cells [3]. The main fuel cell types used for this purpose are: (i) low temperature proton exchange fuel cell (LT-PEM); (ii) high temperature proton exchange membrane fuel cell (HT-PEM); iii) solid oxide fuel cell (SOFC).

SOFCs have a high operating temperature range (650–950 °C [2]), and can operate with hydrocarbon fuels, such as diesel, needing only relatively low reforming and cleaning efforts. This possibility to use the same fuel as the main ICE engine of the truck makes the SOFCs particularly suitable and, currently, the most viable alternative for applications in APUs [4,5]. The main drawback of SOFCs is the long time needed for start-up, which represents one of the challenges for system improvements [5,6].

PEM fuel cells have been found to reduce significantly the environmental impacts of vehicles, especially in terms of GHG emissions when compared to ICE vehicles [7,8], or APUs [9], in particular, it was shown that climate benefits can be substantial with the use of hydrogen originating from renewable energy sources [10,11]. Finally it was observed that the results can strongly depend on the type of electricity (i.e., with fossil, renewable, or nuclear origin), according to the country specific energy mix, that is used to feed the electric and hybrid vehicles [12]. There is a growing interest in PEM fuel cells application as APU, thanks to their lower operating temperatures close to room conditions, and thus shorter start-up times [4]. HT-PEM fuel cells have, obviously, a higher operating temperature (160–180 °C) than LT-PEMs. This has an important consequence on the hydrogen purity requirements: HT-PEMs have a higher tolerance to CO and other impurities, compared to LT-PEMs. Although some studies have been reported on optimization of fuel processing solutions to run LT-PEMs on diesels and jet fuels [13–15], HT-PEMs promise better performances, requiring a less complex system for reforming, together with a better tolerance to impurities [16].

All the above studies imply the use of a reforming process in order to obtain hydrogen from diesel (or other hydrocarbon-based fuels), which represents also the fuel of the main engine. But, in perspective, the use of innovative vehicles not running on fossil fuels, the storage of pure hydrogen on-board would be the simplest solution to avoid the combustion processes.

Storage is still one of the bottlenecks towards a sustainable carbon-free economy based on hydrogen. Among various options, hydrogen storage in the solid state has attracted much attention in recent years [17]. Many different hydride types and compositions have been investigated, as reported by studies concerning both metal and complex hydrides [18–20]. The first studies for industrial use of metal hydrides hydrogen storage were made by Daimler Benz in the eighties by combining metal hydride tanks with ICEs in mini vans [21]. By coupling a hydride tank with a PEM fuel cell, the heat recovered from the latter can be used to desorb the H_2 in the hydrides. This has been proved in the studies by Ungethüm et al. [22] and Urbanczyk et al. [23]. In both cases, an HT-PEM was coupled with a complex hydride tank. In the study by Ungethüm et al. [22] a tank filled with $CsCl_3$ - doped sodium alanate- was coupled with a 1.1 kW HT-PEM fuel cell. The authors focused in particular on heating requirements of the system during start-up: in the first 20 min the fuel cell was operated with H_2 from a hydrogen buffer tank while the FC-hydride tank system was heated up to the operating temperature. In the study by Urbanczyk et al. [23] a Ti-doped sodium alanate hydride tank has been coupled to a 260 W HT-PEM fuel cell. This system was run for several cycles of 3 h each, generating an electric energy of 0.66 kWh. In a study by Rizzi et al. [24], a hydride tank was filled with an intermetallic compound, $LaNi_{4.8}Al_{0.2}$, and coupled with a 1.2 kW PEM fuel cell. This system was operated for more than 6 h at an average power output of 0.76 kW. For 2 h it provided 1 kW output power, and during the running time hydrogen flow increased for the first 100 min (due to start-up) remaining constant for more than 2 h. This system is of interest for its size and because it runs at different load requirements, similarly to the aforementioned APUs.

In the framework of the European project SSH2S, it was developed a solid storage (SS) tank - fuel cell system, and its functioning was demonstrated on a real application, i.e. an APU for a light duty vehicle. As described in detail in [25], unlike the previous studies that coupled PEMs with hydride tanks containing only one type of hydride (i.e. metal hydrides [24] or complex hydrides [23]), the active material in this case is obtained coupling a mixture of complex hydrides (CxH: $2LiNH_2 + 1.1MgH_2 + 0.1LiBH_4 + 3\,wt\%\ ZrCoH_2$) with a hydride of an intermetallic compound (MeH: $LaNi_{4.3}Al_{0.4}Mn_{0.3}$). The tank is composed by several tubes, each consisting of two separate concentric cylindrical compartments containing, respectively, MeH (inner) and CxH (outer), that are separated by a filter mesh made of copper.

This work aims at assessing the environmental impacts of the APU developed in the SSH2S project with a Life Cycle Assessment (LCA) approach. Several LCA studies have been performed on PEM fuel cells [26–29], whereas an LCA on a hydride tank, to our knowledge, has not been published yet, nor a detailed inventory is available. The SSH2S hydride tank is compared with similar commercial systems (type III and IV pressure vessels), which currently represent the most widely used hydrogen storage solutions.

The goal is to assess the environmental performances of the developed system and, with an eco-design approach, to identify the processes mostly contributing to the environmental impacts and to recommend possible ways of reducing them. To complete the analysis, a simplified economic analysis was performed to understand the economic feasibility and to identify the hotspots in the cost structure.

The added value and novelties of this work can be summarised as follows:

- it is the first study on the environmental impacts of a hydrogen solid state storage system
- it compares, with a consistent and comprehensive approach, the environmental performances of solid state storage systems and pressure tanks
- it includes the energy required for hydrogen compression in the comparison of the systems
- it analyses also the costs of the different technologies considered.

2. Materials and methods

This work follows a Life Cycle Assessment (LCA) methodology to assess the environmental impacts of the APU described in detail in [25], comparing the prototype hydride tank used by the APU developed in the SSH2S project with commercial type III and a type IV compressed gas tanks. LCA is a structured and internationally standardized method aimed at quantifying all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with the entire life cycle of any goods or services (“products”) [30]. In this study, the LCA was performed according to ISO 14040 and 14044 standards requirements [31,32], by using the software GaBi 6.3 from PE International [33]. Moreover, the LCA was performed according to a specific guidance document developed within the Project FC-HyGuide of the FCH JU [34]. The FC-HyGuide guidance document [35] is based on, and in line with, the International Reference Life Cycle Data System (ILCD) Handbook on LCA, coordinated by the European Commission's JRC-IES, through the European Platform on LCA. The ILCD Handbook is applicable to a wide range of different decision-contexts and sectors, and therefore needs to be translated to product-specific criteria, guidelines and simplified tools to foster LCA applications in the specific industry sectors. The FC-HyGuide project responded to this need by providing a guidance document