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Impact of Spanish electricity mix, over the period 2008–2030, on the Life Cycle energy consumption and GHG emissions of Electric, Hybrid Diesel-Electric, Fuel Cell Hybrid and Diesel Bus of the Madrid Transportation System

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ABSTRACT

In spite of the advanced research in automotive technology, and the improvement of fuels, the road transport sector continues to be an environmental concern, since the increase in transport demand is offsetting the effects of these technological improvements. Therefore, this poses the following question: what combination of technology and fuel is more efficient in terms of energy consumption and green house gas (GHG) emissions? To fully address this question it is necessary to carry out a Life Cycle Assessment (LCA). This paper presents a global LCA of 4 buses that run on the following fuel types and technologies: (1) Fuel Cell- Hybrid Bus, (2) Hybrid Diesel-Electric Bus (series configuration), (3) Battery Electric Bus and (4) Combustion Ignition Engine Bus. The impact categories assessed are: primary energy consumption, fossil energy and GHG emissions. Among the principal results, we can conclude that the Global LCA of buses (3) and (1) (which are the more sensitive pathways to the electricity mix variation) have for the 2008–2030 period a room for improvement of 25.62% and 28.16% in terms of efficiency of fossil energy consumption and a potential GHG emission reduction of 28.70% and 30.88% respectively.

1. Introduction

In Spain, the transport sector generates one-third of the total GHG emissions, they are growing at a much higher rate than in other sectors [1] and are produced mainly due to the use of fossil fuels. For this reason, different regulations have been implemented in the European Union, as is the case of the Directive 2009/28/EC, which requires a 10% share of energy from renewable sources in the transport sector by 2020 [2]. As the impact of road transport on the environment is a concern but is difficult to measure, it is important to evaluate it through tools as the LCA, which is a compilation and evaluation of the inputs, outputs and potential environmental impacts of a product throughout its entire life cycle (i.e. from cradle to grave) [3]. Moreover its application to the road transport sector provides detailed information about the implementation of alternative fuel/vehicle technologies, which helps to compare them and to detect the weak points in order to improve such technologies.

In this framework, it was considered interesting to carry out a LCA for the operation of four buses in Madrid city, three of which have alternative fuel / propulsion system technology, as follows: (1) Fuel Cell Hybrid Bus that uses hydrogen (is hybrid since it has $LiFePO_4$ batteries and it can operate either just with the energy supplied by these or just with the electric power generated by the PEMFC or with both), (2) Hybrid Diesel-Electric Bus (series configuration), (3) Battery Electric Bus and (4) conventional Diesel Bus. Such analysis was carried out in the context of impact categories of great relevance, such as global warming (caused by greenhouse emissions), and primary and fossil energy consumption [4].

2. Methodology

The LCA methodology was applied to the Life Cycle of the aforementioned buses whose technical specifications are shown in Table 1, in accordance with the ISO 14044 standard which is commonly used in environmental impact assessment [5].

The LCA for a bus consists of the stages shown in Fig. 1 [6].

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Nomenclature

BEB	Battery Electric Bus
CIEB	Compression Ignition Engine Bus
CUTE	Clean Urban Transport for Europe
EMT	Municipal Transport Company (EMT, for its Spanish acronym)
FCHB	Fuel Cell-Hybrid Bus
GHG	greenhouse gases
GLCA	Global Life Cycle Assessment
HDEB	Hybrid Diesel-Electric Bus (series configuration)
H_2 (NGSR)	hydrogen obtained from natural gas by steam reforming
H_2 (WE)	hydrogen obtained by electrolysis of water
ILCD	International Reference Life Cycle Data System
LCA	Life Cycle Assessment
LCAb	Life Cycle Assessment of buses
$LiFePO_4$	lithium iron phosphate
MP	materials production
PEMFC	proton exchange membrane fuel cell
PMC	polymer matrix composite
PM-FPP	production of the materials used in the construction of the fuel production plants
TTW	tank-to-wheel
VA	vehicle assembly and manufacturing
VEL	vehicle end-of-life
VM	vehicle maintenance
WTT	well-to-tank
WTW	well-to-wheel

(a) WTT analysis: it comprises the processes of production, transforming, conditioning and transport of fuels until their supply to buses in refueling stations (Also has been taken into account the production of the materials used in the building of the fuel production plants (PM-FPP)).
(b) TTW analysis: it includes the fuel or energy carrier use by the bus.
(c) LCAb: it analyzes MP, VA, VM and VEL processes.

Finally a GLCA of the buses was made by integrating all the aforementioned stages (a), (b) and (c).

2.1. Calculation methodology of each impact category

The primary energy (MJp) and fossil energy expended (MJfo) expressed in MJ are estimated by adding up all the energy consumption per mass unit or energy of the resource used in the different processes. Then, the result is multiplied by the energy consumption or mass of the resource itself, which provides an indicator that gives information on the energy added to the system. For the emission estimation, the same methodology was applied as in the previous case. The global warming potentials based on 100-year perspective (CO_2 eq. is used as a measurement of Global-warming potential) are 1, 298 and 25 for CO_2, N_2O and CH_4 respectively [7].

2.2. Goal and scope of the study

The main objective of this study is to provide information that enables evaluating quantitatively and comparatively the environmental impact generated in each of the stages of the Life Cycle of the aforementioned buses and the influence of the different electricity mixes proposed in this study (See Table 3) on each fuel/propulsion system pathway. So for accomplish this purpose the different systems analyzed were classified into different scenarios (as shown in Table 2) defined from the combination of the different propulsion systems and fuels used.

As the objective of this study is just to evaluate the influence of the electricity mix over the period 2008–2030 we have focused as much as possible in an accurate collection data of the power electricity generation over this period of time and in the case of the other processes analyzed in this study the just most recent available data were used (without considering a change on time).

So in accordance with the guidelines of the ILCD handbook [8] which remarks that in the case of use less time-representative data, should be done a justification. Therefore, since this is the case for the most of the processes analyzed in this study (except for the power electricity generation process), the justification is that the collection of time representative data for every single process would take too long time and would be too complex mainly because of the lack and unavailability of data in some cases (which can lead to inaccuracies in the analysis) besides, we consider that the influence of these data in the overall analysis are not relevant enough to modify the results in such way that this affects considerably the main objective of this study, which is the appreciation of the influence of the electricity mix on the final results over the period of time afore mentioned. Finally, added to this, the electric power generation process is much more sensitive and prone to change significantly from one year to another in comparison with the other processes analyzed in this study.

2.3. System boundaries, assumptions and functional unit

In this study it is assumed that the buses and fuels were produced within Spain. Therefore, national data have been used as far as possible and when not possible, European data are provided. For the operations conducted outside the Spanish borders, average industry data or data coming from studies published in scientific literature were used. The software tools used were Gabi 4 [9] and GEMIS [10]. The first tool model the energy and mass balance in order to obtain the amount of GHG emissions generated and the primary and fossil energy requirement.

A detailed explanation of how data from GaBi 4 and GEMIS as well as different scientific studies are adapted to the Spanish case (this data become representative of Madrid trough the fuel consumption of the buses tested in this city), is available in the scientific paper [11]. Also has been taken into account the production of materials used to build the facilities where the fuels are produced, since although this contributes to the overall balance less than <1% (known as the cut off criteria) [12] we found interesting to put into perspective the differences regarding to the construction of each fuel production plant in this stage.

Regarding to the construction and maintenance of the infrastructure corresponding to the mobility of vehicles as roads, bridges, illumination systems etc, were excluded from this study. The reason is that although infrastructure is an important factor in the total environmental load of the road transport sector, since it represents about 5–10% [13] of the total energy used for driving a car on a road, its analysis is only recommended when different modes of transport are compared [13] and in this study the comparison is between different technologies and fuels regarding one single mode of transport.