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Energy, environmental and economic comparison of different powertrain/fuel options using well-to-wheels assessment, energy and external costs – European market analysis

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ABSTRACT

The well-to-wheels assessment is widely used in the automotive sector to analyze the efficiency and competitiveness of different powertrain/fuel options. The paper proposes a global index that takes into account both the energy and environmental aspects on an uniform basis, through the assignment of the costs associated to the energy and to the pollutant emissions. The European market is analyzed and other pollutants (NO_x, PM and SO_x) are added to the traditional well-to-wheels evaluations (energy and GHG). The proposed well-to-wheels global index offers a useful place-list that takes into account both energy and environmental aspects and, at the current market conditions, it results that the energy cost prevails (70–85%) over the environmental costs, and among the analyzed external costs, the main contribution is due to the GHG emissions. Natural gas-derived fuels seem to be the most promising. The global index for battery electric vehicle from a European mix are closely linked to the driving range. Conventional biofuels are very critical at present, while significant improvement of the well-to-wheels global index is foreseen for when new generation biofuels will be mature (2030 forecast). In short, even though the proposed global index is not an exhaustive index, it could be a useful tool for decision makers.

1. Introduction

In the last few decades, new powertrain technologies and alternative fuels have been proposed, and many studies have analyzed the influence of these new options on the road transport sector.

There are several reasons behind the opportuneness of starting the transition from the conventional options towards the new ones: the increase in oil prices, the climate change problems, the increasing restrictions on pollutant emissions, the high dependence on oil for the road transport sector, etc.

Many points of view have to be considered: primary sources depletion, environmental impact, economic impact, geopolitical issues, etc. Concentrating the problem to the technological sector, attention is focused on the main topics of global energy balance and environmental impact. The energy balance addresses the management of the primary energy sources (depletion of finite sources, introduction of renewable ones) considering the criteria pertaining to the depletion of primary sources. The environmental impact addresses the effects of the road transport sector on the environment (pollutant emissions, global warming, etc.).

Therefore, a multi-criteria problem has to be dealt with. This multi-criteria comparison of the different available options (both traditional and innovative) is a key point for decision makers, because a powertrain/fuel combination that addresses some criteria might not reach the target for another one. Therefore, some indexes have been proposed to take into account criteria in both the fuel cycle stage (named well-to-tank or WTT) and in the powertrain stage (named tank-to-wheels or TTW). The final objective is usually the integration of these two stages in one criteria, which has been named well-to-wheels (or WTW). It should be noted that originally the acronym WTW only referred to efficiency evaluations, while at present it has been extended to include the environmental aspect, and therefore includes both energy and environmental criteria in the analysis.

One of the most relevant WTW studies has been published by General Motors et al. [1]: first, energy and greenhouse gas emissions were analyzed; then, the study was updated [2], and the emissions of the other pollutants were also added. The WTW evaluations were based on the GREET model, and it should be emphasized that these results were limited to the North American area: the modeled vehicle was a full-sized GM pickup truck, U.S.

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Nomenclature

BEV	battery electric vehicle
c	specific cost
CO_2	carbon dioxide
CNG	compressed natural gas
D	distance
E	energy
EU-mix	combination of different pathways that reflect a European mix of sources that are concurrent to electricity production
FC	fuel cell
FC Hyb	hybrid configuration with electric motor driven by a fuel cell and battery
GHG	greenhouse gas
H2	hydrogen
H2 central	hydrogen production obtained from the steam reforming of natural gas in central plants
H2 on-site	hydrogen production obtained from the steam reforming of natural gas in on-site plants
Hyb	hybrid
ICE	internal combustion engine
ICE Hyb	hybrid configuration with internal combustion engine and electric motor with battery
m	mass
NP	number of pollutants
NG	natural gas
NO_x	nitrogen oxides
PM	particulate matter (refers to diameters of less than 10 microns)
SO_x	sulphur oxides
TTW	tank-to-wheels acronym
TTW	tank-to-wheels indexes
WTT	well-to-tank acronym
WTT	well-to-tank indexes
WTW	well-to-wheels acronym
WTW	well-to-wheels indexes
1st gen	1st generation biofuels
2nd gen	2nd generation biofuels

Subscripts and superscripts

e	energy
Ex	external
f	fuel
GLOBAL	the WTW index that includes both energy and external costs
p	pollutant
t	total
x	expended
€	cost
*	superscript meaning that the WTT index refers to a reference distance
'	superscript meaning that the energy WTT index is the ratio between the total energy and the fuel energy

Color association in the figure bars

Red	oil-derived fuels (gasoline and diesel, also named traditional fuels)
Blue	natural gas-derived fuels (CNG and H2)
Green	biofuels (bio-ethanol and bio-diesel)
Yellow	Electricity (EU-Mix)

driving cycles were adopted, and the reference point for the pollutants was the U.S. EPA database.

A European study, similar to [1], was conducted by L-B-Systemtechnik GmbH (LBST), General Motors et al. [3]. As far as WTT values are concerned, European plant efficiencies were adopted (e.g. in the case of oil refining). As far as TTW values are concerned, a smaller reference vehicle was chosen as being more representative of the European context, and the European Driving Cycle (EDC) was considered.

Successively, another European WTW study was published by EUCAR, CONCAWE and Joint Research Centre of the EU Commission [4], in which both the energy and GHG emissions were calculated. A new version of the study has been published in 2007 [5-7]. New pathways have been added and the previous pathways have been updated. The 2007 report is probably the best study (both the most complete and most updated) concerning the European market, and a very wide range of alternative fuel and powertrain options have been considered.

Many research papers have been published in the literature: in particular, in the last few years, hydrogen pathways and its use in PEMFC-based powertrains have been compared with other fuels and powertrains. Wang [8] studied the impact of a fuel cell vehicle using the GREET model, and evaluated the WTW for both energy and emissions; he observed that a WTW analysis is necessary for an adequate evaluation of the powertrain/fuel combination, and in particular that the main differences in energy and GHG emission are due to the fuel pathways. It should be emphasized that the results of this paper are again limited to North America. Mizsey and Newson [9] compared five powertrain/fuel combinations, considering WTW efficiency, GHG emissions and investment costs; the best efficiency was obtained for the hybrid internal combustion engine (ICE Hyb) fed with diesel, while the best WTW GHG emissions was obtained for the FC, operated with compressed H2, produced on a centralized plant; the lowest investment costs were obtained for the ICE, while the on-board fuel-reformer solutions offered poor results for all aspects. Hekkert et al. [10] have used the WTW (efficiency and CO_2 emissions) to analyze the replacement of crude oil with natural gas. They compared 15 different both traditional and new technology options: their results indicated that FC + compressed H2 (produced by steam reforming of natural gas) led to the highest GHG reduction (up to 40% compared to current practice) thanks to one of the highest energy efficiencies; however, in the case of liquefied H2, the GHG emissions rose dramatically. The ICE Hyb fed by diesel was also interesting: it took first place for WTW efficiency and second place for GHG reductions. Silva et al. [11] have proposed a useful model to calculate the TTW (energy consumption and emissions) of conventional and alternative fuels. As far as WTT is concerned, they adopted a commercial life cycle analysis software. They then analyzed a case study related to two real buses in the Portugal capital: a diesel bus and a compressed natural gas bus. The WTW results revealed that diesel is better, in terms of energy consumption, while natural gas had lower GHG emissions. Zamel and Li [12] have compared ICE and FC in Canada, using a total life cycle (both a vehicle cycle and a fuel cycle). The ICE was considered to be fuelled with gasoline, and the FC with hydrogen. Four different hydrogen production processes were analyzed, two via steam reforming (in a central plant or in a refueling station) and two via electrolysis (electrical power from coal or nuclear). The analysis was conducted on both energy consumption and GHG emissions and the main conclusion was that FC was better than ICE, except when hydrogen was obtained via electrolysis using coal. However, the capital cost of FC was estimated to be higher than ICE by around 30%. The same