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Exergy and environmental comparison of the end use of vehicle fuels: The Brazilian case

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ABSTRACT

In this work, a comparative exergy and environmental analysis of the vehicle fuel end use is presented. This analysis comprises petroleum and natural gas derivatives (including hydrogen), biofuels (ethanol and biodiesel), and their mixtures, besides of the electricity generated in the Brazilian electricity mix, intended to be used in plug in electric vehicles. The renewable and non-renewable unit exergy costs and CO_2 emission cost are proposed as suitable indicators for assessing the renewable exergy consumption intensity and the environmental impact, and for quantifying the thermodynamic performance of the transportation sector. This allows ranking the energy conversion processes along the vehicle fuels production routes and their end use, so that the best options for the transportation sector can be determined and better energy policies may be issued. It is found that if a drastic CO_2 emissions abatement of the sector is pursued, a more intensive utilization of ethanol in the Brazilian transportation sector mix is advisable. However, as the overall exergy conversion efficiency of the sugar cane industry is still very low, which increases the unit exergy cost of ethanol, better production and end use technologies are required. Nonetheless, with the current scenario of a predominantly renewable Brazilian electricity mix, based on more than 80% of renewable sources, this source consolidates as the most promising energy source to reduce the large amount of greenhouse gas emissions which transportation sector is responsible for.

1. Introduction

In 2011, transportation sector in Brazil consumed 74 millions of tons of oil equivalent (toe), almost 30% of national energy demand, and was responsible for 56% of the consumption of petroleum-derived fuels. Road subsector itself attained 91.7% of the total energy consumption in transportation sector, equivalent to 27.5% of the national energy consumption, and became the largest energy consumer by subsector [1]. In Brazil, almost half of the energy used in transportation sector comes from diesel oil (48.6%), followed by gasoline (28.2%) and ethanol (14.5%). Natural gas (2.2%), kerosene (4.8%) and fuel oil (1.3%) are used in a small quantity, and only 0.4% of electricity generated in Brazilian electricity mix is used in transportation sector. Brazilian transportation fleet is composed of automobiles (59%), motorcycles (27%), commercial light vehicles (10%), heavy trucks (3%) and passenger buses (1%) [2], which are mainly powered by four types of vehicle technologies. The vehicles dedicated to gasoline C run on a mixture of gasoline A (pure gasoline) and 18–27.5% *v*/*v* of anhydrous ethanol. Since the establishment of the National Alcohol Program (PROALCOOL) in 1975, the addition of anhydrous ethanol to pure gasoline used in automotive vehicles is compulsory and dedicated gasoline A vehicles are not further commercialized in Brazil. In 2003, the automotive industry introduced the flex-fuel vehicles, which can operate with a mixture of gasoline C and hydrated ethanol (4.5% *v*/*v* of water) in any proportion, and manufactured to tolerate up to 100% of hydrated ethanol [3]. Dedicated hydrated ethanol vehicles were commercialized until 2007, when the production was discontinued mainly owed to the wide acceptance of flex-fuel technology. In fact, 18.54 millions of flex-fuel vehicles were licensed up to the year 2012, which represents almost half of the whole fleet of light vehicles in Brazil [4]. Other technologies, such as compressed natural gas (CNG) vehicles (converted from either gasoline or flex-fuel engines, with almost half (42%) of the fleet located in Rio de Janeiro state [5]) and diesel-cycle engines (used only by commercial and passenger light vehicles with a minimum capacity load of 1000 kg [2]) are also commercialized. Since 2012, the addition of 5–7% *v*/*v* of biodiesel to diesel oil intended to

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Nomenclature

$\%C_{fossil}$	percentage of fossil embodied carbon ($kg_{CO2,fossil}/kg_{CO2,stoich}$)
A	vehicle frontal projected area (m^2)
a	acceleration ($m\ s^{-2}$)
B	exergy (kJ), exergy rate/flow rate (kW)
b	specific exergy (kJ/kg)
c	unit exergy cost (kJ/kJ)
C	consumption data (L/100 km)
c_{CO2}	CO_2 emission cost (gCO_2/kJ)
C_d	drag coefficient
CC	vehicle autonomy (km/L)
c_p	specific heat capacity (kJ/kg-K)
c_R/c_{NR}	ratio between the renewable to non-renewable exergy cost
C_{RR}	rolling resistance coefficient
e	orthonormal basis
g	gravity acceleration ($9.8\ m\ s^{-2}$)
$I_{CO2,fossil}$	fossil emission factor ($kg_{CO2,fossil}/kg_{fuel}$)
$I_{CO2,stoich}$	stoichiometric emission factor ($kg_{CO2,stoich}/kg_{fuel}$)
LHV	lower heating value (kJ/kg)
m_v	vehicle mass (kg)
m_F	fuel mass (kg)
m_{CO2}	specific direct CO_2 emissions (gCO_2/MJ)
M_{CO2}	direct CO_2 emissions (gCO_2/s)
P	pressure (bar, atm)
RPM	revolution per minute (min^{-1})
R_u	universal gas constant (8.314 kJ/kmol-K)
SW	transportation service work rate
T	temperature (K, °C)
υ	speed (m/s)
$\%V$, v/v	volumetric fraction
V	volume (m^3)
W	work (kJ), power (W)
x	traveled distance (km)
y	mole fraction (%)

Greek symbols

η	efficiency
φ	chemical exergy (b^{CH}) to lower heating value (LHV) ratio
γ	activity coefficient
ρ_{ar}	air density $1.18 kg/m^3$ at P_o = 1 atm, T_o = 25 °C
ρ	density (kg/m^3)
θ	slope angle (rad.)

Subscripts and superscripts

CH	chemical exergy (kJ/kg)
CO_2	carbon dioxide emission
ex	exergy
F	fuel
i	i-th mixture component
mix	mixture
NR	non-renewable
o	reference standard states (25 °C, 1 bar)
R	renewable
S	transportation service
T	total
υ	vehicle

be used in transportation sector in Brazil is compulsory, and this quantity is expected to increase to 10% in 2020 [2]. Biodiesel was introduced in the Brazilian market in 2003, and since then its production capacity has been expanded dramatically, mainly based on soy, palm and tallow as raw materials.

Notwithstanding the advances achieved in efficiency and the environmental impact mitigation policies, the transportation sector, as a major consumer of the primary energy of the country, still corresponds to a dominant source of energy degradation and greenhouse gas (GHG) emissions. For instance, total CO_2 emissions from Brazilian energy mix reached 395.8 millions of tons in 2011, of which 48.5% were produced by the transportation sector, almost twice as much as industry emissions (24.9%) [1]. It suggest that any improvement achieved by the transportation sector could not only favorably affect the national energy economy, but also help to mitigate the environmental impact produced along the different supply chains and end use of the vehicle fuels. Thus, it is necessary an appropriate methodology to assess and compare in a rational way the performance of the routes of the vehicle fuel production and end use by means of a suitable tool, and thereby pursue and prioritize the most environmentally friendly energy sources. In this work, a previously introduced methodology [6–11] that serves the purpose is implemented, and the renewable and non-renewable exergy cost and CO_2 emission cost of the *transportation service* (i.e. the exergy required to overcome the resistive forces and to attain a desired kinetic energy) in the Brazilian transportation sector is calculated. Some authors have addressed energy and exergy based analysis on the transportation sector around the world. Seckin et al. [12] developed the analysis of transportation sector in Turkey by using the Extended Exergy Accounting (EEA), obtaining a global exergy efficiency as low as 36%, mainly due to the high proportion of non-renewable energy sources used in the transportation mix. Zarifi et al. [13] presented an overall energy and exergy evaluation of Iranian transportation sector. An overall exergy efficiency of 21.19% in 2009 was reported. Sánchez et al. [14] presented a global life cycle assessment of 4 buses that run on: (1) fuel cell-hybrid bus, (2) diesel-electric hybrid bus (series configuration), (3) battery electric bus and (4) combustion ignition engine bus. It was concluded that the technologies with more sensitive pathways to the electricity mix variation (1 and 3) present the highest potential improvements by 2030. Battery and hybrid electric vehicles were compared with conventional vehicles and fuel cell electric vehicles by Mierlo et al. [15]. It was highlighted that from a well-to-wheel emission point of view, the results are positive and favor the battery electric vehicles (EV). Notwithstanding, other studies have pointed out that EV promotion could be counterproductive in areas where electricity is primarily produced from lignite, coal, or even heavy oil combustion. At best, with such electricity mixes, local pollution reductions may be achieved rather than reducing them globally [16]. A comparative assessment carried out by Ma et al. [17] on the life cycle greenhouse gas (GHG) emissions of battery EVs in Europe also identified the need to correctly assign the relevant emissions associated to the electricity consumed in battery-powered vehicles.

2. Methodology

Exergy is defined as the maximum available work that can be obtained from a thermodynamic system through its interaction with the environment by means of reversible processes until the equilibrium state (mechanical, thermal and chemical) with the environment components is attained. Total exergy accounts for potential (^{P}), kinetic (^{K}), thermo-mechanic (physical, ^{PH}) and chemical (^{CH}) exergy components, each one calculated by using ((1)–(4)), respectively: