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Life-cycle analysis of energy and greenhouse gas emissions of automotive fuels in India: Part 2 – Well-to-wheels analysis

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A B S T R A C T

In this second of the two-part study, the results of the Tank-to-Wheels study reported in the first part are combined with Well-to-Tank results in this paper to provide a comprehensive Well-to-Wheels energy consumption and greenhouse gas emissions evaluation of automotive fuels in India. The results indicate that liquid fuels derived from petroleum have Well-to-Tank efficiencies in the range of 75–85% with liquefied petroleum gas being the most efficient fuel in the Well-to-Tank stage with 85% efficiency. Electricity has the lowest efficiency of 20% which is mainly attributed due to its dependence on coal and 25.4% losses during transmission and distribution. The complete Well-to-Wheels results show diesel vehicles to be the most efficient among all configurations, specifically the diesel-powered split hybrid electric vehicle. Hydrogen engine configurations are the least efficient due to low efficiency of production of hydrogen from natural gas. Hybridizing electric vehicles reduces the Well-to-Wheels greenhouse gas emissions substantially with split hybrid configuration being the most efficient. Electric vehicles do not offer any significant improvement over gasoline-powered configurations; however a shift towards renewable sources for power generation and reduction in losses during transmission and distribution can make it a feasible option in the future.

1. Introduction

India is the fourth largest energy consumer in the world. The primary energy consumption of around 316.29 million tons of oil equivalent was reported for the year 2010–2011; with the transportation sector accounting for 17.5% of the total energy consumption making it the second largest energy consuming sector in the country [1]. Passenger vehicles account for 13% of all the registered motor vehicles in the country during the year 2011 [2]. Road transport accounted for 124 kg out of the total 135 kg of carbon dioxide emissions per capita from the transportation sector for the year 2011 [3]. Therefore, a life cycle analysis of various fuels, in other words, a WTW (Well-to-Wheels) analysis is required to assess the use of energy and the impact of emissions in various vehicle–fuel combinations.

A study of the literature shows several country-specific WTW studies for automotive fuels specific to USA, Europe, China, Switzerland and Norway. A detailed WTW analysis of a full size pick-up truck for North American conditions was conducted by General Motors in 2001 [4] and this was further improved in 2005 [5]. These studies involved 124 pathways using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model; which has since then become the basis for many WTW studies. The WTW results show that advanced vehicle technologies offer great potential for reducing petroleum use, GHG (greenhouse gas) emissions and pollutant emissions. It was also found that hybrids fuelled with CNG (compressed natural gas) achieve larger reductions in GHG emissions as compared to diesel hybrids, whereas the reverse trend is observed in case of fuel economy.

Another previous study pertaining to USA [6] published life-cycle analysis of new automobile technologies for the year 2020. This study evaluated potential of new fuel and vehicle technologies in 2020 on the basis of life-cycle energy use, life-cycle GHG emissions and consumer cost per unit distance driven. It was predicted that IC engine or fuel cell based hybrid vehicles would be most efficient and lowest emitting technologies. This study was further extended to predictions for the year 2035 to quantify the potential future energy and environmental impacts of new and improved

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List of abbreviations

BEV	battery electric vehicle
FCV	fuel cell vehicle
GHG	greenhouse gas
GWP	global warming potential
HEV	hybrid electric vehicle
PHEV	plug-in hybrid electric vehicle
ICE	internal combustion engine
IDC	Indian Drive Cycle
LPG	liquefied petroleum gas
NG	natural gas
CNG	compressed natural gas
ONGC	oil and natural gas corporation
T&D	transmission and distribution
TTW	tank-to-wheels
WTT	well-to-tank
WTW	well-to-wheels

fuel-vehicle technologies in the light-duty vehicle fleet [7]. The study concluded that 30–50% reduction in fuel consumption is feasible over the next 30 years. This was expected through improved gasoline and diesel engines, gasoline hybrids, and reduction in vehicle weight and drag in the short term. In the long term, it was predicted that plug-in hybrids and hydrogen fuel cell vehicles may have significant impact on fuel use and emissions.

Another WTW study [8] in the European Context concerns predictions for the year 2020 and beyond. Comprehensive WTW energy consumption and emissions for conventional petroleum and advanced fuel pathways on a C-segment sedan car platform were presented. It was found that WTW GHG emissions for current CNG vehicles lie between those of gasoline and diesel, whereas current LPG (liquefied petroleum gas) vehicles provide a small WTW GHG saving as compared to that of gasoline and diesel vehicles. The evaluation of hydrogen fuel produced from NG (natural gas) showed that hydrogen from NG used in a fuel cell in the 2020+ horizon has potential to produce half the GHG emissions of a gasoline vehicle. A study by Torchio et al. [9] described a WTW analysis in the European context introducing a new global index by assigning costs to energy, emissions and other factors. This study concludes that usage of natural gas-based fuels and hybridization as promising options compared to conventional gasoline and diesel fuel vehicles. A WTW life cycle analysis for alternative fuel and vehicles in China was conducted by Shen et al. [10]. For reduction in energy consumption and GHG emissions, this study points towards electrification of vehicles via HEVs (hybrid electric vehicles), PHEVs (plug-in hybrid electric vehicles) and BEVs (battery electric vehicles) parallelled by development of low carbon sources for electricity production. Another life cycle analysis for China was conducted by Wang et al. [11]. This work compared the FCV (fuel cell vehicle) with H_2 produced from 5 different pathways and EVs with conventional ICE (internal combustion engine) vehicles. It was concluded that FCVs using hydrogen from electrolysis of water powered by Chinese electricity grid and EVs cannot achieve energy saving and emissions reduction. Another WTW analysis by Yazdanie et al. [12] concerned the operation of conventional and alternative passenger vehicles in Switzerland. This analysis showed that HEVs using alternate fuels particularly biogas and CNG resulted in remarkable reductions in WTW energy and GHG emissions over a conventional gasoline-powered IC engine vehicle. A WTW study by Svensson et al. [13] focused on a medium-sized passenger car in the Norwegian energy system. This study showed that the BEV powered by the European electricity matrix to be similar in GHG emissions to those of a gasoline HEV. It was also concluded that hydrogen must be produced from renewable sources or from NG including CO_2 capture and storage, for fuel cell cars to be superior to hybridized gasoline/diesel cars in terms of energy consumption and emissions.

A study on electric powertrains by Kromer et al. [14] again highlights that IC engine-based HEVs are to play a key role in the ultimate transit to complete electric technologies. Another study by Katranšik [15] concluded that hybridization has a smaller impact on WTW CO_2 emissions in medium duty trucks as compared to passenger cars after analysing a medium duty truck on different drive cycles, charging modes and CO_2 intensities of electricity production. Recently, a study by Waller et al. [16] calculated the maximum possible WTW efficiencies associated with three possible transportation pathways using natural gas. Direct conversion use of CNG in a combustion engine; reforming natural gas to produce H_2 for use in FCVs and production of electricity in a combined cycle power plant to power a BEV were reported to offer similar theoretical maximum efficiencies of the order of 84–87%. A similar study was also conducted by Curran et al. [17] for direct and indirect NG-based pathways. Both studies conclude that the overall WTW efficiency is mainly dependent on the combustion technology associated with the ICE or the stationary power plant in case of electricity generation.

In summary, it is clear from the literature review that WTW analysis has been effective tool in assessing energy use and GHG emission impact of alternative fuel-vehicle options. What stands out is that the results of a WTW analysis are highly country-specific, and the exact nature of the results in quantitative terms can vary significantly from country to country mainly due to the different energy mix of the specific region. The energy use and emissions associated with fuel production is very different under Indian conditions as compared to other countries. Also, the electricity generation mix for India is very different from that of other countries, as the Indian electricity grid is dominated by energy from coal and natural gas. Further, electricity transmission and distribution losses are much higher in India as compared to other countries. All of the above reasons underscore the need for a comprehensive lifecycle analysis of automotive fuels in India comparing various fuel and powertrain options.

A subcompact passenger car is chosen for this analysis, as passenger cars in India are dominated by small cars (mini-compact, subcompact and compact cars) which constitute 60% of the total number [18], and the need for electric mobility is being recognized [19]. Moreover, there is no reported WTW analysis for subcompact cars, as earlier WTW studies for various countries have considered mid-sized passenger cars, SUVs and trucks. The TTW (Tank-to-Wheels) results from Part-1 paper of this two-part study are combined with the WTT (Well-to-Tank) results reported in this present paper to provide the comprehensive WTW results for various automotive fuels. The next few sections describe the methods used, WTT results for various fuels and WTW results for various fuel-powertrain combinations, followed by a summary of the results.

2. Methods

The GREET (Greenhouse Gases, Regulated Emissions and Energy Use in Transportation) model (version 2011) developed by ANL (Argonne National Laboratories) was employed to simulate the energy use and emissions involved during the analysis [20]. Lower calorific values of the various fuels are used throughout the analysis. The WTT stage covers the energy and emissions associated with (1) Extraction, cultivation and processing of the