Transportation Research Part D 51 (2017) 340–350

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: A global perspective

JongRoul Woo [a], Hyunhong Choi [a], Joongha Ahn [b,*]

[a] Institute for Data, Systems, and Society (IDSS), Massachusetts Institute of Technology (MIT), 77 Massachusetts Avenue, Cambridge, MA 02139-4307, United States
[b] Samsung Economic Research Institute, 29thFloor, Samsung Life Seocho Tower, Seocho 2-dong, Seocho-gu, Seoul 137-955, South Korea

ARTICLE INFO

Article history:
Received 12 April 2016
Revised 8 September 2016
Accepted 30 January 2017
Available online 21 February 2017

Keywords:
Well-to-wheel
Greenhouse gas emission
Electric vehicle
Electricity generation mix

ABSTRACT

In the transport sector, electric vehicles (EVs) are widely accepted as the next technology paradigm, capable of solving the environmental problems associated with internal combustion engine vehicles (ICEVs). However, EVs also have environmental impacts that are directly related to the country's electricity generation mix. In countries without an environmentally friendly electricity generation mix, EVs may not be effective in lowering greenhouse gas (GHG) emissions. In this study, we analyzed the extent to which the GHG emissions associated with EVs differs among 70 countries in the world, in relation to their domestic electricity generation mix. Then, we compared the results with the GHG emissions from the ICEVs. Countries with a high percentage of fossil fuels in their electricity generation mix showed high GHG emissions for EVs, and for some of these countries, EVs were associated with more GHG emissions than ICEVs. For these countries, policies based on the positive environmental impact of EVs may have to be reconsidered. In addition, different policies may need to be considered for different vehicle types (compact car, SUV, etc.), because the ability of EVs to reduce GHG emissions compared to that of ICEVs varies by vehicle type.

1. Introduction

Since the latter part of the 20th century, climate change has become a global issue. Governments and people around the world noticed the negative effects that excessive greenhouse gas (GHG) emissions can have on our nature and society. Consequently, they are continuing their efforts to reduce the use of fossil fuels, which are considered the main source of emission of GHGs and other pollutants.

The transport sector is a major contributor to the world's fossil fuel consumption and GHG emissions. In 2013, the energy spent in the transport sector comprised 27.6% of the total energy consumption in the world and 92.6% of this amount was based on the consumption of oil products (IEA, 2016). In addition, CO_2 emissions generated by the transport sector were 22.9% of the total CO_2 emissions in the world (IEA, 2015a). As a consequence, there is now a tacit consensus worldwide on the need to change the technological paradigm in the transport sector to improve the air quality and reduce GHG

* Corresponding author.
E-mail addresses: jroul86@mit.edu (J. Woo), hongchoi@snu.ac.kr (H. Choi), joongha.ahn@gmail.com (J. Ahn).

http://dx.doi.org/10.1016/j.trd.2017.01.005
1361-9209/

emissions. Given this situation, EVs are considered as the energy efficient solution to the environmental problems associated with the conventional Internal Combustion Engine Vehicles (ICEVs) because the former produce zero tail pipe emissions.

Market penetration of BEVs has been very slow and restricted until recently, because of their shortcomings such as a short traveling distance, long charging time, unaffordability, and under-developed or non-existent charging infrastructure (Larminie and Lowry, 2003; Nilsson, 2011; Bishop et al., 2014; Wikström et al., 2014; Donateo et al., 2015). However, the annual sales of EVs have been increasing rapidly in the recent years. With a significant reduction in the prices of EVs, in addition to governmental regulations related to GHG (mainly CO_2) and fuel efficiency all around the world, the market demand for EVs is growing notably. In 2011, the annual global BEV sales were approximately 36,000 units. This number increased by over 50% in 2012, exceeding 55,000 units. In 2013, the annual sales were beyond 100,000 units, and in 2014, they exceeded 160,000 units with the global BEV stock of over 350,000 units (IEA, 2013, 2015c). In Norway, more than 10% of the annual car sales in 2014 comprised BEVs (IEA, 2015c). In addition, global car sales are expected to rise by about 40% from 2013 (83 million units) to 2020 (117 million units) and 41% of the increased demand (14 million units) is expected to consist of Plug-in Hybrid Electric Vehicles (PHEVs) and BEVs (JD Power, 2013).

Although EVs are now considered as the next technology paradigm in the transport sector, their actual effect on the environment is directly related to the electricity generation mix used in a particular country. Therefore, for countries that do not have an environmentally friendly (in terms of GHG emissions) electricity generation mix, some argue that EVs may not be very effective in reducing GHG emissions (Faria et al., 2013; Freire and Marques, 2012; Doucette and McCulloch, 2011; Tomic and Kempton, 2007; Huo et al., 2009; Wu et al., 2007; Granvskii et al., 2006; Helms et al., 2010; Varga, 2013; Nichols et al., 2015; Bickert et al., 2015; Huo et al., 2015; Rangaraju et al., 2015; Tamayao et al., 2015; Jochem et al., 2016).

Some studies linking the GHG emissions associated with EVs to a particular country's electricity generation mix have been conducted recently. Varga (2013) analyzed the CO_2 emissions of EVs and ICEVs considering Romania's electricity generation mix. He pointed out that even if the EV market penetration were increased in accordance with the Romanian government's EV supply policy, it would not lead to a reduction in the CO_2 emissions in the country. Faria et al. (2013) selected three countries, each of which depends heavily on a particular type of energy, namely fossil fuels (Poland), nuclear energy (France), and renewable energy (Portugal), in their electricity generation mix and compared the GHG emissions of EVs in these countries. Hawkins et al. (2013) claimed that considering the average electricity generation mix, EVs in Europe will help reduce the GHG emissions by 10–24% compared to ICEVs. Onat et al. (2015) considered the electricity generation mix of the 51 states in the United States, and compared the GHG emissions of ICEVs, hybrid electric vehicles (HEVs), PHEVs, and BEVs. The results showed that, according to the average electricity generation mix scenario (EPA, 2009), the GHG emissions calculated for BEVs were the lowest in 24 states and according to the near-future marginal electricity generation mix scenario (Hadley and Tsvetkova, 2009; Thomas, 2012), BEVs were not associated with the lowest emissions of GHGs in any of the states. According to Onat et al. (2015), a high market penetration of BEVs in the near future would be an "unwise" strategy based on the existing and near-future scenarios.

One of the limitations of the above-mentioned studies is that their analyses are based on a single country, mainly a European or a North American country. To clarify whether or to what extent BEVs could help solve global GHG emission-related problems, such as climate change, these studies will need to be extended to more countries to obtain a global viewpoint. Furthermore, to compare the GHG emissions associated with EVs with those of ICEVs from a global viewpoint, the entire supply chain of the power source for different vehicular technologies (electricity or oil) must be considered.

Although studies evaluating the environmental effect of EVs from a global viewpoint have not yet been actively pursued, Doucette and McCulloch (2011) compared the CO_2 emissions of ICEVs and those associated with BEVs in the United States, China, India, and France by considering their electricity generation mix. However, these researchers did not use the actual EV data, instead, they used the "estimated" specifications of the hypothetical EVs. This was because their study was carried out in 2011, and at that time, there were not many commercialized EVs in circulation. Moreover, even though their study included some major countries, it still falls short of obtaining a global-level implication of the environmental effects of BEVs.

In this study, the vehicle technology of interest is conventional motorization, as represented by both gasoline and diesel ICEVs, and the electric vehicle technology represented by Battery Electric Vehicles (BEVs). The study covers the top 70 countries, including those from Central & South America, Africa, Middle East, and Asia & Pacific, in terms of their CO_2 emissions in 2012 (EIA, 2016). These countries together generate 97% of the world's total CO_2 emissions and 96.7% of the world's total electricity. By comparing the GHG emissions from BEVs and ICEVs in these countries, we will assess the environmental effects of BEVs from a global viewpoint. Also, by dividing these countries into seven regional categories (Africa, Asia & Pacific, Europe, Eurasia, Middle East, North America, South & Central America), we will identify some regional differences in the environmental impacts of BEVs. For the list of countries studied and the regional divisions, see Appendix A.

The objective of this study is to evaluate the extent to which the GHG emissions associated with EVs change according to each country's electricity generation mix and the differences between the GHG emissions associated with EVs and ICEVs in each country by performing a well-to-wheel analysis. The study utilizes the specifications of EVs and ICEVs that are currently being sold in the market, which makes the analysis more realistic and reliable than the previous studies that used the estimated or virtual specifications for vehicles. The findings will have significant implications on the environmental impacts of BEVs at the country-, regional-, and global-level.

The remainder of this paper is organized as follows. Section 2 presents the methodology and data used for the analysis. Section 3 contains the results and discussion of the analysis. Finally, Section 4 presents the conclusions and some policy implications of this study.