Applied Energy 230 (2018) 135–147

Contents lists available at ScienceDirect

Applied Energy

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

Well-to-wheel greenhouse gas emissions of battery electric vehicles in countries dependent on the import of fuels through maritime transportation: A South Korean case study

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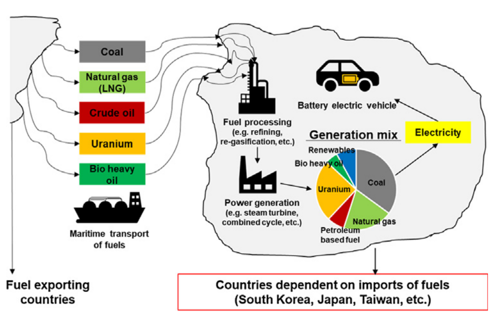
HIGHLIGHTS

- A case of countries dependent on fuel imports via maritime transportation is studied.
- 5 power generation fuels, 10 generation methods, and 2 electric grids are analysed.
- Importing raises the GHG emissions of power generation fuels, especially natural gas.
- WTW GHG emissions of BEVs with each generation fuel and method are calculated.
- The average WTW GHG emissions of BEVs are lower than those of ICEVs and HEVs.

GRAPHICAL ABSTRACT

Well-to-wheel greenhouse gas emissions of BEVs in countries dependent on the import of fuels through maritime transportation.



ARTICLE INFO

Keywords:
Well-to-wheel analysis
Battery electric vehicle
Fuel importing countries
Life cycle analysis
Primary energy sources
Greenhouse gas

ABSTRACT

Well-to-wheel (WTW) analysis of battery electric vehicles (BEVs) has been mainly performed in the U.S., China, and Europe, which are countries that can produce sizable amounts of fuels or import additionally required fuels through land transportation. However, the situation characterizing these countries is far different from that of countries dependent on the import of fuels through maritime transportation, such as Japan, South Korea, and Taiwan, because the dependence on fuel imports through maritime transportation affects not only the energy mix but also the complexity and results of WTW analysis. In addition, determining the WTW greenhouse gas (GHG) emissions of driving BEVs in these countries is very important since these countries have large amounts of GHG emissions and strong interests in the widespread adoption of BEVs. Therefore, unlike previous studies, this study evaluates the WTW GHG emissions of BEVs in South Korea as an example of such countries. To perform WTW analysis of BEVs, comprehensive life cycle analyses of five power generation fuels (coal, natural gas, petroleum-based fuel, uranium, and bio heavy oil) are conducted. In addition, ten different power generation technologies and two different electric grids (mainland and the Jeju Island) in South Korea are analysed. The fuel economies of BEVs and conventional vehicles are also considered for evaluating the WTW GHG emissions. The result of this study shows that import processes commonly increase the life cycle GHG emissions of power generation fuels. The GHG emissions of natural gas from the upstream process are ~40% higher than those of the U.S due to the liquefaction and regasification required for importing natural gas. However, although natural gas produces large amounts of GHG emissions from the upstream process, the electricity generated from natural gas still produces the lowest GHG emissions among the fossil fuels like other countries due to the high efficiency

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https://doi.org/10.1016/j.apenergy.2018.08.092
Received 14 February 2018; Received in revised form 26 July 2018; Accepted 16 August 2018

Nomenclature

BEV	battery electric vehicle
ICEV	internal combustion engine vehicle
HEV	hybrid electric vehicle
WTW	well-to-wheel
WTT	well-to-tank
TTW	tank-to-wheel
LCA	life cycle analysis
GHG	greenhouse gas
CO_2	carbon dioxide
CH_4	methane
N_2O	nitrous oxide
CO	carbon monoxide
ST	steam turbine
CC	combined cycle
FC	fuel cell
ICE	internal combustion engine
WWS	wind, water, solar

of combined cycle systems. The life cycle GHG emissions of electricity of the Korean mainland and Jeju are calculated to be 578 g CO_2 eq/kWh and 544 g CO_2 eq/kWh, respectively, which are higher than that of the EU and lower than that of the U.S. and China. Driving BEVs in South Korea was found to have advantages of 90–110 g CO_2 eq/km and 50–60 g CO_2 eq/km on average over driving internal combustion engine vehicles (ICEVs) and hybrid electric vehicles (HEVs), respectively, not only on the Korean mainland but also on Jeju Island. Because the GHG emissions from the upstream process of major power generation fuels and the life cycle GHG emissions of the electricity from major power generation technologies are determined in this study, these results are expected to be informative for other countries, which may have different detailed generation mixes, in similar situations.

1. Introduction

Battery electric vehicles (BEVs) are considered to be one of the most promising vehicle technologies for reducing greenhouse gas (GHG) emissions in the transportation sector. To make BEVs to be used more dominantly in the transportation sector, various researches have been performed on batteries and charging infrastructures, such as improving the performances [1,2] and control [3,4] of batteries, lowering the cost of batteries [5], shortening the charging time [6,7], and optimizing the charging infrastructures [8,9]. BEVs are especially advantageous in that they are highly efficient and produce no emissions from the tailpipe. However, the electricity, which is the fuel for BEVs, is generated from various primary energy sources (coal, natural gas, crude oil, uranium, etc.), and therefore, driving BEVs also causes the production of primary energy sources and the electricity generation from these primary energy sources. These processes do produce GHG emissions. Therefore, the amount of GHG emissions from driving BEVs has usually been evaluated by life-cycle-based approaches, such as well-to-wheel analysis, life cycle risk assessment, ecological footprint, and material flow analysis [10]. Though the focus and the objectives of the analysis might be different among these approaches, all the methodologies provide the information of lifetime environmental implications of battery electric vehicles.

Among these approaches, well-to-wheel (WTW) analysis, which is focused on assessing the environmental impacts of transportation fuels and corresponding vehicle technologies, has usually been adopted when evaluating the life cycle GHG emissions from driving BEVs. WTW analysis assesses GHG emissions from the well (where the primary energy sources are obtained) to the tank (where the fuel of the vehicle is stored) of the vehicle (well-to-tank, i.e., WTT) and then from the tank to the wheels of the vehicle (tank-to-wheel, i.e., TTW).

Thus far, studies that have evaluated the environmental impacts of BEVs through WTW analysis have concentrated on the U.S., China, and Europe [11–17]. Because whether BEVs are effective in reducing GHG emissions and how effective they are depend on the country and regional characteristics, these studies were conducted based on the corresponding situation. Moreover, recently, to calculate the WTW GHG emissions of BEVs from more microscopic perspectives, WTW analyses in these countries have been conducted not only on nations but also on states or cities [18–23]. For example, Huo et al. performed WTW analysis of BEVs in China and found that, on a national average, BEVs can reduce the WTW GHG emissions per kilometer traveled by 20% compared to internal combustion engine vehicles (ICEVs) [18]. In addition, they calculated WTW GHG emissions for each province and determined provinces better suited for using BEVs. Ke et al. conducted WTW analysis of BEVs on Beijing, which is a city of China, and found that BEVs can reduce WTW CO_2 emissions by 32% compared to ICEVs mainly due to the shift from coal to gas in local power plants [19]. Onat et al. performed WTW analysis of BEVs compared with hybrid electric vehicles (HEVs) and ICEVs at the state level in the U.S. [20]. They found that BEVs are the lowest carbon-intensive vehicle option in 24 states, whereas HEVs are the best option in 17 states. Casals et al. conducted WTW analysis of BEVs in Europe and determined countries that were better suited in Europe for the adoption of BEVs. They found that, for example, in France and Norway, BEVs can reduce WTW GHG emissions compared to ICEVs, whereas in Germany and the UK, BEVs do not offer immediate WTW GHG emissions reductions compared to ICEVs [21].

However, the U.S., China, and Europe can produce sizable amounts of primary energy in their own countries or can import additionally required energy though land transportation, which is a relatively easy way of importing fuels. Fuel-producing countries usually adopt a strategy to utilize domestically produced fuels dominantly for power generation for ensuring energy security as well as promoting the economy. For example, the U.S. and China are the world's largest natural gas and coal producers, respectively [24]. These domestically produced natural gas and coal represent large shares of power generation in the U.S. and China, respectively.

On the other hand, the situation of countries that have to import most fuels is different. These countries cannot adopt a strategy of using domestically produced fuels and usually import diverse forms of fuels from various countries to reduce political and economic risks [25]. This fact makes the WTW analysis of BEVs in fuel-importing countries more complex.

Moreover, the situation of countries dependent on the import of fuels only through maritime transportation, such as Japan, South Korea, and Taiwan in East Asia, is far more different. Fig. 1 shows the map of these countries. As shown in the figure, Japan and Taiwan are island countries and South Korea is a geopolitically island-like country. According to the governments of these countries, over 90% of the total primary energy supply in these countries is imported from overseas through maritime transportation; Japan imported 94%, South Korea imported 95%, and Taiwan imported 98% in 2014 [26–28]. The difficulty of maritime transportation affects not only the energy mix by influencing the price of each primary energy source but also the life