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Well-to-wheel water footprints of conventional versus electric vehicles in the United States: A state-based comparative analysis

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ABSTRACT

Today, increasing levels of water demand become a particularly serious challenge for many countries, especially since water is an essential element for production of transportation fuels. Unfortunately, no research efforts as of now have been directed specifically toward understanding the fundamental relationship between the adoption of electric vehicles (EVs) and water demand. This research aims to fill this knowledge gap by analyzing the water consumption and withdrawal impacts resulting from the increased usage of alternative vehicle technologies in the United States. 5 vehicle types - Internal Combustion Vehicles (ICVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEV20, PHEV40) and Battery Electric Vehicles (BEVs) - are analyzed across 50 U.S. states with 3 different electricity generation mix profiles: the state-based average electricity generation mix, the state-based marginal electricity generation mix, and a hypothetical electricity generation mix consisting entirely of solar-powered charging stations. The well-to-wheel (WTW) life cycle analysis is used for the water footprint calculations. In worst case, BEVs may consume up to 70 times more water than ICVs. BEVs with solar charging have the lowest levels of water consumption and withdrawal and can reduce transportation water footprint by up to 97%. In most of the states, the marginal electricity generation mix has higher water consumption and withdrawal values than those of the average electricity generation mix. In particular, the authors suggest the use of BEVs with solar charging for states with the highest water-stressed areas (California (CA), Arizona (AZ), Nevada (NV), Florida (FL), etc.), and recommend the inclusion of incentives by federal and state governments for these states.

1. Introduction

The United States of America (U.S.A) has one of the largest transportation networks in the world with very large fuel consumption and travel characteristics (Transportation Energy Data Book, 2012). While the U.S. transportation sector's energy consumption was observed to be 27.8% of the total energy consumption in the U.S., the petroleum-based share of the transportation energy consumption mix was 92.8% (Transportation Energy Data Book, 2012). In the U.S. passenger transportation system, approximately 90% of the total vehicle miles traveled (VMT) was attributed to light-duty vehicles (US DOT, 2013). Combustion emissions from U.S. automobiles and light-duty trucks accounted for approximately 60% of greenhouse gas (GHG) emissions from the U.S. transportation sector (Zhao et al., 2016), or 17% of total U.S. carbon emissions (Samaras and Meisterling, 2008). Due to the aforementioned statistics, energy consumption and global climate change have become topics of considerable interest for sustainable vehicle transportation (Ercan et al. 2016, 2017), and there is now a growing trend in use of electric cars in U.S. highways (Onat et al., 2015a, 2016c). However, vehicle water footprints are also becoming increasingly important due to the fundamental connection between water consumption/withdrawal and electricity production, as well as the adoption of energy- and carbon-efficient electric vehicle technologies, which have a direct impact on regional water demand levels (Bartos and Chester, 2014; King and Webber, 2008; Stillwell et al., 2011). According to the 2001 National Energy Policy, the growing U.S. population and economy will require 393,000 MW of new energy generating capacity by the year 2020, which in and of itself will put additional pressure on domestic water resources.

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Acronyms

ADP	Abiotic Depletion Potential
AER	All-electric range
AP	Acidification Potential
CD	charge-depleting
EP	Eutrophication Potential
EPA	United States Environmental Protection Agency
ET	Eco-toxicity
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FDP	Fossil depletion potential
FTP	Federal Test Procedure
GHG	Greenhouse gas
GREET	The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	Global warming potential
HEV	Hybrid Electric Vehicle
HTTP	Human Toxicity Potential
HWFET	Highway Fuel Economy Test
ICV	Internal Combustion Vehicle
kWh	Kilowatt hour
LCI	Life Cycle Inventory
LDV	light duty vehicle
Li-ion	Lithium-ion
M&R	Maintenance and repair
MDP	Mineral depletion potential
NAICS	North American Industry Classification System
NHTS	National Household Travel Survey
NiMH	Nickel–metal hydride
ODP	Ozone layer depletion
PHEV	Plug-in Hybrid Electric Vehicle
POFP	Photochemical oxidation Potential
PPI	Producer Price Index
PV	Photovoltaic
SC03	the EPA SC03 or air conditioning test drive cycle
UF	Utility Factor
US06	the EPA US06 (also: “aggressive” or “high speed”) drive cycle
USGS	United States Geological Survey
VMT	Vehicle miles traveled

Furthermore, the expected increase in the U.S.A population will significantly boost the demand for light-duty vehicles, in turn simultaneously increasing domestic energy and water consumption levels.

Water use can take two forms such as consumption and withdrawal. Therefore, it is important to understand the difference between these two forms. Water consumption is defined as the amount of water obtained from a surface water or groundwater source that is not directly returned to its original source. For example, water evaporation from cooling at a thermoelectric steam power plant is an example of water consumption. In addition, water withdrawal is the amount of water obtained from a surface water or groundwater source that is used in a process and then sent back to system. For example, the abstracted water used for cooling at a coal power plant and then returned to the catchment that it was originally withdrawn from is an example of water withdrawal (Madani and Khatami, 2015; Shaikh et al., 2017). Electricity production from fossil fuels and nuclear energy requires a total of 190 billion gallons of water per day, accounting for 39% of all freshwater withdrawals in the U.S., 71% of which goes to fossil-fuel electricity generation alone. Additionally, coal plants account for nearly 52% of the total U.S. electricity generation mix, requiring 25 gallons of water withdrawal per kWh of electricity generated from these coal plants (Sandia National Laboratories, 2015). Overall, coal, nuclear and biomass energy are responsible for the largest water withdrawal levels in the U.S. (Fthenakis and Kim, 2010). Among these energy sources, coal-based power generation is responsible for approximately 50% of the total water withdrawal, followed by irrigation, municipal water usage, and other categories (Fig. 1).

According to the U.S. Department of Energy, until 2020, the expected population growth ranges between 20% and 50% in most water-stressed regions of the U.S.A (Sandia National Laboratories, 2015). This growth, in turn, will also substantially increase the demand for passenger cars and vehicle miles of travel, so it will be essential to gain a detailed understanding of the interdependencies of water-reliant vehicle systems and promote the adoption of water- and energy-efficient BEVs. Although the number of electric vehicles in U.S. has demonstrated an increasing trend, many concerns regarding the regional water footprint of electric vehicles remains unaddressed. To better assess the energy-use-related water footprints of emerging electric vehicle technologies, this research aims to quantify the water consumption and withdrawal levels of internal combustion vehicles (ICVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs) in the United States. Considering the fact that, at the regulatory level, the well-to-wheel (WTW) analysis is the most commonly applied life cycle assessment method, which is used to assess the environmental impacts in transport. WTW analysis of electric vehicles is dominantly used for policy making in the European Union, China and U.S.A (Moro and Lonza, 2017; Moro and Helmers, 2017). To this end, the current paper primarily focuses on the water footprint analysis of the vehicle operation phase excluding other vehicle life-cycle phases such as the vehicle part manufacturing phase(s), the vehicle maintenance and repair phases, and the vehicle end-of-life phase. This assumption is made based on past studies showing that the vehicle operation phase is responsible for the highest energy consumption (76%–85% of the total life cycle energy consumption), whereas the contributions of other life-cycle phases were found to be considerably lower compared to the operation phase (Onat et al., 2014b).

2. Life cycle assessment

Life Cycle Assessment (LCA) methods have been used extensively to analyze vehicle technologies and provide significant insights for developing sustainable transportation strategies (Onat, 2015a, 2015b; Onat et al., 2016b). LCA aims to quantify the environmental impacts of a product or a process over every phase of its entire life cycle, including raw material extraction and processing, manufacturing, operation, and end-of-life recycling and/or disposal (Kucukvar et al., 2014; Noori et al., 2013; Onat et al., 2014c, 2014d). The LCA analytical process primarily consists of goal and scope definition, inventory analysis, impact assessment, and interpretation of LCA results (Kucukvar et al., 2016a, 2016b, 2015; Onat et al., 2014a). LCA is widely used in recent literature as a methodological framework to estimate environmental footprints (Egilmez et al., 2016) and several studies were found focusing on the water footprints of electricity (Shaikh et al., 2017), corporations (Ercin et al., 2011), diet options (Vanham et al., 2013), animal products (Ercin et al., 2012), crop production (Mekonnen and Hoekstra, 2014;