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Life-cycle assessment of greenhouse gas and air emissions of electric vehicles: A comparison between China and the U.S.

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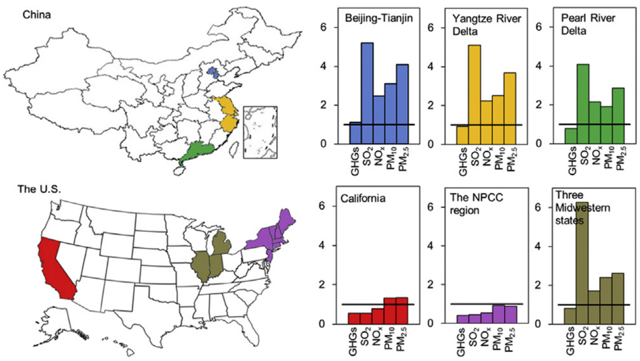
HIGHLIGHTS

- Electric Vehicles (EVs) are a promising low-carbon solution to save oil worldwide.
- We analyzed the fuel-cycle emissions of EVs in 6 key regions of China and the U.S.
- EVs can reduce emissions in US California and the northeast states significantly.
- EVs may raise pollutant emissions in China's 3 regions and the US Midwest states.
- EVs will offer better environmental benefit as power plants are cleaner in future.

GRAPHICAL ABSTRACT



Fuel-cycle emission factors of EVs in 2012 (gasoline vehicles=1)

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ABSTRACT

We evaluated the fuel-cycle emissions of greenhouse gases (GHGs) and air pollutants (NO_x, SO_2, PM_{10}, and $PM_{2.5}$) of electric vehicles (EVs) in China and the United States (U.S.), two of the largest potential markets for EVs in the world. Six of the most economically developed and populated regions in China and the U.S. were selected. The results showed that EV fuel-cycle emissions depend substantially on the carbon intensity and cleanness of the electricity mix, and vary significantly across the regions studied. In those regions with a low share of coal-based electricity (*e.g.*, California), EVs can reduce GHG and air pollutant emissions (except for PM) significantly compared with conventional vehicles. However, in the Chinese regions and selected U.S. Midwestern states where coal dominates in the generation mix, EVs can reduce GHG emissions but increase the total and urban emissions of air pollutants. In 2025, EVs will offer greater reductions in GHG and air pollutant emissions because emissions from power plants will be better controlled; EVs in the Chinese regions examined, however, may still increase SO_2 and PM emissions. Reductions of 60–85% in GHGs and air pollutants could be achieved were EVs charged with 80% renewable electricity or the electricity generated from the best available technologies of coal-fired power plants, which are futuristic power generation scenarios.

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1. Introduction

Advanced electric drive vehicles (EVs), which refer primarily to plug-in hybrid electric vehicles and pure battery electric vehicles, represent a promising solution to energy insecurity and greenhouse gas (GHG) emissions. Approximately 0.113 million EVs were sold globally in 2012 (International Energy Agency, 2013). The International Energy Agency's (IEA's) Electric Vehicles Initiative (EVI), which includes 15 countries, aims to reach combined annual EV sales of 5.9 million by 2020 (International Energy Agency, 2013).

Of the 15 EVI countries, China and the United States (U.S.) are two important EV markets; each accounts for more than 10% of global EV sales (CATARC, 2011; Gong et al., 2013; Argonne National Laboratory, 2013). Both governments have made ambitious goals for EV deployment in the near future. The U.S. government has announced the aim of having one million EVs on the road by 2015 (U.S. Department of Energy, 2011). In 2012, China's State Council proposed that China should achieve accumulated sales of half a million new-energy vehicles (namely EVs) by 2015, and five million by 2020 (China's State Council, 2012). In 2014, China and the U.S. released the U.S.-China Joint Announcement on Climate Change, which states that China and the U.S. will cooperate intensively in the fields of low-carbon technologies, including electric vehicles. Currently, China and the U.S. are the world's two largest markets for vehicles, and they could become the largest markets for EVs in the future.

By using electricity, EVs are able to displace petroleum-based fuels. However, recent life-cycle studies have raised concerns that the use of EVs might increase GHG and air pollutant emissions, compared with conventional gasoline internal combustion engine vehicles (ICEVs). In addition, the magnitudes of the increases are related significantly to the cleanness of regional power mixes (Huo et al., 2010, 2013; Hawkins et al., 2013; Holdway et al., 2010; Zehner, 2013; Ji et al., 2012). China and the U.S. have significant coal shares in their national generation mixes (76% and 38% in 2012, respectively), which can influence negatively the GHG and air emission performances of EVs.

Both China and the U.S. are major GHG contributors and in each country the power and transport sectors are major air pollution contributors (Zhang et al., 2007, 2009; Lu et al., 2010; Zhao et al., 2013; U.S. EPA, 2012a, 2013). Technological advancements related to these sectors in both countries can result in environmental benefits at the national, or even global, level. Furthermore, China and the U.S. are making efforts to mitigate their national GHG emissions and have made firm commitments to decrease the absolute amount of national NO_x and SO_2 emissions. China is also facing an urgent challenge regarding PM pollution, and power plants have been identified as key targets for improving urban and regional air quality (Zhang et al., 2012; Wang et al., 2012). As China and the U.S. are intending to put a large number of EVs on the road, it is essential to understand to what extent the use of EVs could impact GHG and air pollutant emissions. This is not only an interest of the academic community but is also a concern of policy makers.

Our goal was to answer the above question by simulating life-cycle GHG (CO_2, CH_4, and N_2O) and air pollutant (SO_2, NO_x, PM_{10}, and $PM_{2.5}$) emissions of EVs operating in China and the U.S. As fuel-cycle (namely well-to-wheels) stages are estimated to account for the majority of life-cycle GHG and air pollutant emissions (Hawkins et al., 2013), we focused on the fuel-cycle stages. Two time horizons were analyzed: current (2012) and future (2025). We also examined a best available technique (BAT) scenario and a low-carbon (LC) renewable electricity scenario to explore the maximum potential of EVs in reducing GHG and air pollutant emissions. This work concentrates mainly on battery electric vehicles (hereafter referred to as EVs); conventional gasoline ICEVs were included as baseline vehicles.

Because energy-use characteristics (*e.g.*, generation mixes) vary significantly across regions in both countries, to generate more location-specific implications, this life-cycle analysis focused on six typical EV operation regions (Fig. 1). The three Chinese regions are the Beijing-Tianjin region (BTR); the Yangtze River Delta (YRD, covering Shanghai, Zhejiang, and Jiangsu); and the Pearl River Delta (PRD, Guangdong), which are the regions of China most developed economically and together accounted for nearly 50% of EV sales in China in 2010 (Gong et al., 2013; Wu et al., 2012). The three U.S. regions are California (CA), the Northeast Power Coordinating Council (NPCC) region (New York, Maine, Vermont, New Hampshire, Massachusetts, Connecticut, and Rhode Island), and three Midwestern states (Illinois, Indiana, and Michigan), which are among the largest regions in terms of population, vehicle sales, and future EV purchase potential in the U.S. For each country, the three regions together account for approximately one-third of national gross domestic product (GDP), population, vehicle stock, and vehicle sales (State Statistical Bureau of China, 2012a, 2013; U.S. Census Bureau, 2013; U.S. Department of Transportation (2013); NADA, 2013; U.S. Department of Commerce, 2013; The World Bank, 2013).

2. Methods and boundary

The life-cycle analysis was conducted with the functional unit of 1 mile driven by an average car under real-world driving conditions. The GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model (http://greet.es.anl.gov/) was applied to perform the life-cycle analysis. The GREET was designed for the U.S., but during previous work, we developed a version of GREET for China's ICEVs and EVs (Huo et al., 2010, 2013). In this work, we produced the life-cycle emissions of EVs for both China and US.

To explore the impacts of EVs on urban air quality, we separated urban emissions from total emissions. In GREET, the urban emissions of an industrial process (or vehicle activities) are calculated by multiplying the total emissions of the process by its urban share. The urban shares are determined by the locations of facilities (Wang, 1999; Huo et al., 2009). We recently updated the urban share in the GREET model based on statistical data from 2010. For China, the urban share of the emissions from power plants was determined by assuming that the power plants that are located in the urban areas defined by the MODIS (Moderate Resolution Imaging Spectroradiometer) land use map (Schneider et al., 2009) are urban power plants. Because we are examining the environmental impact of urban cars, the share of vehicle activities occurring in urban areas is set to be 100%.

The fuel-cycle stages examined include feedstock mining/recovery and transport, fuel production and transport/transmission, and the fuel consumed in engines. Of these fuel-cycle stages, electricity generation and vehicle operation are the dominant emission stages of EVs and ICEVs, respectively, and thus they were examined in more detail.

3. Electricity generation

With almost the same total amount of electricity generated, China and the U.S. are the world's two largest electricity producers and the two countries together accounted for approximately 40% of the global electricity generation during the past 30 years (Fig. 2) (State Statistical Bureau of China, 2012b; U.S. Energy Information Administration, 2013a; International Energy Agency, 2012). Both China and the U.S. have a generation mix dominated by fossil fuels (80% in China and 70% in the U.S.), which makes electricity