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Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States

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HIGHLIGHTS

- Driving patterns and electricity generation mix influence vehicle preferences.
- EVs are found to be least carbon-intensive vehicle option in 24 states.
- HEVs are found to be the most energy-efficient option in 45 states.
- EVs across the board are unfavorable in the marginal electricity mix scenario.
- Use of renewable energy to power EVs/PHEVs is crucial.

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ABSTRACT

Electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (HEVs) are often considered as better options in terms of greenhouse gas emissions and energy consumption compared to internal combustion vehicles. However, making any decision among these vehicle options is not a straightforward process due to temporal and spatial variations, such as the sources of the electricity used and regional driving patterns. In this study, we compared these vehicle options across 50 states, taking into account state-specific average and marginal electricity generation mixes, regional driving patterns, and vehicle and battery manufacturing impacts. Furthermore, a policy scenario proposing the widespread use of solar energy to charge EVs and PHEVs is evaluated. Based on the average electricity generation mix scenario, EVs are found to be least carbon-intensive vehicle option in 24 states, while HEVs are found to be the most energy-efficient option in 45 states. In the marginal electricity mix scenario, widespread adoption of EVs is found to be an unwise strategy given the existing and near-future marginal electricity generation mix. On the other hand, EVs can be superior to other alternatives in terms of energy-consumption, if the required energy to generate 1 kW h of electricity is below 1.25 kW h.

1. Introduction

Analyses of alternative vehicle technologies, energy sources, transportation fuels, and more efficient ways to use resources have become increasingly popular topics in the literature and industry. The need for sustainable and more efficient transportation systems is growing in the U.S. due to increasing concerns about global climate change, national energy security, and rising oil prices. The transportation sector has been one of the most significant sources of greenhouse gas (GHG) emissions and energy consumption in the U.S. The energy consumption and GHG emissions of the transportation sector account for approximately 28% of the U.S. total, and the transportation sector is responsible for 67% of total U.S. petroleum consumption and it consumes around 1.5 times more petroleum than the total U.S. petroleum production. The majority of the energy used in the transportation sector, about 93% of the total energy consumption mix, is provided through petroleum. On the other hand, for the U.S. transportation sector, light duty vehicles comprise 63% of total petroleum use, 59% of total energy use, and 60% of total GHG emissions [1]. In 2012, the largest sources of transportation GHG emissions were passenger cars with 43.1% of the transportation sector's total, whereas light duty trucks (including sport utility vehicles (SUVs), pickup trucks, and minivans) were responsible for 18.4% of the total. These two categories together represent the total light duty vehicle fleet in the U.S. [2]. In this study, alternative passenger vehicle technologies are investigated due to their greater potential for reducing transportation related

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GHG emissions. As the U.S. transportation sector heavily relies on petroleum and is a major contributor to the nation's GHG emissions, various alternative passenger vehicle technologies (such as hybrid, plug-in hybrid, and electric vehicles) have been developed to minimize these impacts. Furthermore, federal governments, national agencies in the U.S., and international organizations promote adoption of alternative vehicle technologies and support efforts aiming to develop environmentally friendly and economically viable policies [3–6]. According to President Obama's 2013 climate action plan, increasing fuel economy standards and developing advanced transportation technologies are prioritized strategies for reducing the environmental impacts of the U.S. transportation sector [4]. In this regard, national laboratories, various institutions, and research centers evaluate these options comprehensively and try to develop effective policies to minimize environmental impacts [7–13].

Among the various vehicle alternatives, electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) are often considered as better options than internal combustion vehicles (ICVs) in terms of GHG emissions and energy consumption. In reality, however, making such a decision among these vehicle options is not so straightforward due to temporal and spatial variations, such as regional driving profiles and the sources of the electricity used. For example, the electricity used to power EVs or PHEVs might come from an energy source that is more energy and carbon intensive than petroleum. PHEVs use an on-board battery to travel in electric mode and consume gasoline when the battery charge is depleted. Therefore, the all-electric range (AER), or the range for which a PHEV can operate in electric mode, is one of the most important parameters to determine its energy use and GHG emission rate. In addition to the effects of the AER, the length of vehicle trips determines the fraction of total vehicle travel that is powered by either gasoline or electricity. According to the National Household Travel Survey (NHTS) in 2009, vehicles that traveled less than 48 km comprised 63% of the daily passenger vehicle miles traveled (VMT) in the U.S [14]. Therefore, a significant amount of daily travel can be powered by electricity, and using PHEVs can reduce the impacts of gasoline use. On the other hand, this percentage might be different depending on the driving characteristics of a specific region. Hence, the inclusion of these spatial variations is crucial when deciding which vehicle technology is the most suitable for the associated region in terms of GHG emissions and energy use.

2. Literature review and motivation

A comprehensive literature review is undertaken to compare the scope and main focus of various studies addressing the environmental impacts of ICVs, HEVs, PHEVs, and EVs. In total, 38 different peer-reviewed articles, mainly life cycle assessment (LCA) studies, are evaluated based on their scope, investigated vehicle technologies, and selected environmental impact categories. A detailed evaluation of these papers is shown in Table S1 in the Supplementary Information (SI) file available at the journal's website. Although there are a wide range of studies evaluating the environmental performance of EVs and PHEVs, there are relatively few studies covering spatial variations. The importance of the electricity generation mix and driving patterns has been stressed in previous studies [15–25]. Samaras and Meisterling [16] analyzed the life cycle GHG emissions of PHEVs considering various electricity mix scenarios and the U.S. average driving patterns. Kelly et al. [17] investigated the impacts of U.S driving patterns, demographic variations, and different charging scenarios on the GHG emissions of PHEVs on a national scale. Ma et al. [15] conducted a full life cycle assessment of EVs considering marginal electricity mixes and driving conditions for the United Kingdom and California. One of the most comprehensive studies found in the literature was conducted by Faria et al. [18], in which country-wide temporal and spatial variations for France, Portugal, and Poland are taken into consideration, and their impacts on the GHG emissions and energy use of EVs and PHEVs were thusly highlighted. Raykin et al. [23] examined how driving patterns influence the GHG emissions of PHEVs under various electricity generation mix scenarios in Ontario, Canada. Huo et al. [25] investigated the energy use and GHG emissions of EVs considering the various regional electricity generation mixes in China, and their analysis revealed that EVs are not the best option to reduce GHG emissions in China due to the high GHG intensity of China's current electricity generation mix. However, the focus of all of these studies was either on a national level or for a specific region, and most of them did not include marginal electricity mix scenarios. Also, a majority of the studies focused on the use phase only, in what is known as well-to-wheel analysis. This study differs from previous LCA studies by making comparisons across 50 states, including their representative average and marginal electricity generation mixes and regional driving patterns. Additionally, GHG emissions and energy consumption during vehicle and battery manufacturing and vehicle maintenance are also included in the scope of this study. The objectives of this study are as follows:

(1) to investigate the impacts of regional driving patterns and electricity generation mix scenarios (marginal and average) on the energy use and GHG emissions of alternative passenger vehicle technologies currently available in the market,
(2) to highlight how these spatial and temporal variations affect the carbon footprint and energy consumption performances of these vehicles,
(3) to demonstrate the relative impacts of battery and vehicle manufacturing on GHG emissions and energy consumption within the total life cycle of vehicles,
(4) to investigate potential GHG emission reductions and energy savings considering the potential market size and market penetration scenarios.

3. Methodology

LCA is a widely accepted method to quantify the environmental impacts of products or processes throughout the production, use, and end-of-life phases [26]. Traditionally, there are two main methodologies in LCA literature: process based (P-LCA) and input–output based (IO-LCA). On the other hand, sometimes a combination of these two is found as more powerful way of conducting LCA; in the literature, this is known as hybrid LCA [27–31]. In this study, P-LCA, hybrid LCA, and IO-LCA were utilized depending on the associated content. The production and maintenance of each of these vehicles, as well as the upstream emissions from the gasoline supply chain, were analyzed with Economic Input–Output Life Cycle Assessment model (EIO-LCA) [32], while the electric power supply and battery manufacturing phase were analyzed with P-LCA. Additional information about LCA methods are provided in the SI document. Data used in this study is collected from publicly available sources such as the U.S. Life Cycle Inventory (LCI) database [33], the GREET vehicle cycle model [34], the eGRID database [35], and the National Household Travel Survey (NHTS) [14]. Fig. 1 shows the system boundary of the analysis.

In this study, five passenger vehicle types representing different vehicle technologies have been comparatively evaluated based on their energy consumption and GHG emissions for 50 states in the U.S. All vehicles are ranked based on their GHG emissions and