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# Electric vehicle cost, emissions, and water footprint in the United States: Development of a regional optimization model

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ABSTRACT

The life cycle cost and environmental impacts of electric vehicles are very uncertain, but extremely important for making policy decisions. This study presents a new model, called the Electric Vehicles Regional Optimizer, to model this uncertainty and predict the optimal combination of drivetrains in different U.S. regions for the year 2030. First, the life cycle cost and life cycle environmental emissions of internal combustion engine vehicles, gasoline hybrid electric vehicles, and three different Electric Vehicle types (gasoline plug-in hybrid electric vehicles, gasoline extended range electric vehicle, and all-electric vehicle) are evaluated considering their inherent uncertainties. Then, the environmental damage costs and the water footprint of the studied drivetrains are estimated. Additionally, using an Exploratory Modeling and Analysis method, the uncertainties in the life cycle cost, environmental damage cost, and water footprint of studied vehicle types are modeled for different U.S. electricity grid regions. Finally, an optimization model is coupled with Exploratory Modeling and Analysis to find the ideal combination of different vehicle types in each U.S. region for the year 2030. The findings of this research will help policy makers and transportation planners to prepare our nation's transportation system for the influx of electric vehicles.

## 1. Introduction

### 1.1. Background and scope of study

Human-induced climate change continues to result in extreme weather conditions [1]. Almost 97 percent of scientists believe in human-induced climate change [2], contributing to an increasing level of attention given to the mitigation and adaptation of its effects. Policymakers around the globe are tackling how to curb the causes of climate change at both national and international scales. One of the ways to mitigate the effects of climate change is to reduce GHG (greenhouse gas) emissions. Therefore, the reduction of GHGs has become a policy-driver for many societies due to the growing threat of global temperature and storm intensity increase.

The environmental and emissions impacts of the transportation sector are directly relevant to ameliorating the effects of climate change. Managing transportation-related emissions will play a significant role in reducing total emitted GHGs. With demand for passenger vehicles continuing to grow, one way to mitigate transportation sector emissions is to increase the proportion of alternative fuel vehicles in the fleet. Among these new technologies, EVs (electric vehicles), including hybrid and all-electric vehicle types, have stimulated tremendous interest both in the U.S. and globally. The share of EVs in the transportation fleet has increased dramatically in recent years, mainly due to battery improvements and because electricity will be the most efficient and cheapest transport fuel in the future [3,4]. Also, compared to other alternative fuel technologies, battery electric vehicles establish the most promising transport integration technology [5]. These technology improvements, coupled with the potential to store electricity in vehicles as an integral part of the modernization of the electric grid, continue to increase the importance of EVs for future transportation.

Although the Obama administration has backed off of its goal of one million electric vehicles on the road by 2015 [6], others have set a goal for the share of electric-powered passenger vehicles to reach 20% of the U.S. new sales market by the year 2030 [7]. This trend makes it vital to study EVs in further detail. Policy-makers, scientists, and manufacturers typically understand the importance of LCC (life cycle cost) and LCEE (life cycle environmental emissions) of EVs in their ongoing discussions. However, often missing from

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the dialogue is the EDC (environmental damage cost) and WFP (water footprint) of EVs. EDC is estimated using LCEE and the unit cost of environmental degradation for each air pollutant. In fact, access to more comprehensive information might result in a completely different policy direction. On the other hand, there are many uncertain variables in evaluating the LCC, EDC, and WFP of EVs. This study first aims to improve upon the life cycle analysis of different EV technologies by addressing primarily the uncertainties in these metrics simultaneously. Then, using the most probable range of values, this study aims to predict the most appropriate combination of EVs and ICEVs that should be on the road in 2030, considering economic costs, environmental damage costs, and water footprint.

Here, five different vehicle types are compared and analyzed: ICEV (Internal Combustion Engine Vehicle), HEV (Gasoline Hybrid Electric Vehicle), PHEV (Gasoline Plug-in Hybrid Electric Vehicle), EREV (Gasoline Extended Range Electric Vehicle), and BEV (All-Electric Vehicle). For PHEVs, when the battery is preliminarily used and especially in hard acceleration conditions, the gasoline engine facilitates driving the vehicle. An EREV is a type of PHEV with a larger battery that powers the vehicle until depleted, at which point the vehicle switches to gasoline power. Therefore, PHEVs consume gasoline during charge depleting mode, while EREVs do not. For the purposes of this study, it is assumed that PHEVs have an all-electric range of 10 miles and EREVs have an all-electric range of 40 miles.

This study distinguishes itself from previous efforts in several ways. First, the AFLEET (Alternative Fuel Life-Cycle Environmental and Economic Transportation) tool, developed by the ANL (Argonne National Laboratory), is used to find the LCC of different EVs. This tool was recently released and has yet to be used extensively by the research community. This study builds on AFLEET to create a new model called the EVRO (Electric Vehicles Regional Optimizer), which considers all possible uncertainties of LCC to account for the whole picture of EV costs. Second, although there have been some efforts to analyze the environmental damage costs of EVs, this effort integrates uncertainties into the EDC using the variability in the LCEE as well as the unit environmental damage cost of each air pollutant. Third, previous studies frequently use an average U.S. electricity mix in their analysis. Here, the LCC, EDC, and WFP of EVs is estimated for different electricity generation mixes, based on 22 U.S. electric grid regions. Finally, a stochastic optimization tool is coupled with EMA (Exploratory Modeling and Analysis) to find the best EV drivetrain mix for each U.S. electric grid region for the year 2030.

The rest of the paper is structured as follows: First, the existing literature on the LCC, LCEE, and WFP of EVs is described. Second, the methodology and general assumptions are described, the concept of EDC is discussed and added to the analysis through consideration of the LCEE of different EV drivetrains, and the mathematical content of the EVRO (Electric Vehicles Regional Optimizer) model is discussed. Then, the uncertainties are presented and explained. Finally, the results and implications of the EVRO model are illustrated and ideas for future study are presented.

### *1.2. Life cycle cost, life cycle environmental emissions, and water footprint of EVs*

The LCC (Life Cycle Cost) and LCEE (Life Cycle Environmental Emissions) of EVs have been extensively studied, and there are several studies on the WFP (Water Footprint) of EVs in the literature. A summary of the existing literature is described in this subsection.

Often cited in the literature is the detailed LCC analysis of EVs by ANL. ANL compares several vehicle cost, fuel price, and government subsidy scenarios to understand the future role of EVs in the vehicle market [8]. However, they admit that predicting the future role of EVs in the market has some complexities, due to the inherent uncertainty of oil prices, lack of knowledge about future customers' behavior toward new technologies, the performance and cost of future technologies, and future governmental action. A summary of the rest of the literature examining the LCC of EVs is indicated in Table 1.

The LCEE of EVs has received substantial attention in the literature. However, various authors have made differing assumptions about vehicle weights, battery sizes, propulsion and fuel efficiency, how broadly to draw a boundary around the LCA (life cycle analysis), and electricity mix. One study developed a model to estimate the life cycle emissions using the primary vehicle data such as weight, year of manufacture, engine technology, and fuel type used [9]. Some authors do not specify the emissions intensity of the electricity used to charge. Treatment of the production, operation, and disposal life cycle stages also varies, with some studies reporting on each stage individually and some rolling all stages into one life cycle value. Table 1 summarizes many of these examples.

EV emissions are highly dependent on generation source. Most authors have assumed a U.S. national electricity mix, with some authors performing sensitivity analyses to investigate low carbon or high carbon generation sources. The Union of Concerned Scientists published a report that investigated emissions from charging electric vehicles by region, and showed how integral electric generation mix is to the operational emissions of EVs [10]. Pre-combustion and upstream GHG emissions of the power plant fuel mix for the U.S. can contribute an extra 9% above direct power plant emissions on average, resulting in an additional 54 g CO2e/kWh for the average U.S. mix [11]. Additionally, transforming the transport fuel system to 100 percent renewable energy sources would require multiple measures and close integration of transport within the larger energy system [12]. Therefore, understanding the future trend of transport and electricity fuel sources plays a vital role in the decision-making surrounding alternative fuel vehicles. Please see Table 1 for a summary of literature on LCEE of the studied vehicle types.

The water use of power plant operations is an important aspect of the life cycle cost analysis because use of water in electricity production prevents others from using the water for other purposes, and this resource is highly constrained in some parts of the U.S. The freshwater footprint of water withdrawal becomes a key factor in the siting of new power plants and in water resource planning [25]. The concepts of water and energy are fundamentally connected: 49% of the total fresh water withdrawal in the U.S. is caused by thermoelectric power generation. At present, the transportation industry is not heavily reliant on water, since 95% of transportation fuels are petroleum fuels. However, the share of EVs in the fleet is increasing and reliance on water for generating electricity will increase in the near future [26]. Therefore, considering WFP as a decision variable is one of the goals of this research. The water consumption and water withdrawal associated with gasoline and electricity are taken from the literature. The sources used are explained in detail in the methodology section (Section 2.3.3).

## 2. Research methodology

In this section, the methodology framework is explained. The following subsections describe the conceptual basis and mathematical contents of the methodology. First, the developed EVRO (Electric Vehicle Regional Optimizer) and its relationship to the