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Exploring the suitability of electric vehicles in the United States

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ABSTRACT

This study explores suitability of battery electric vehicles in the United States by considering their potential market share and operations costs as well as the state-specific variations in electricity generation profiles, given current government policies and the social acceptability of the technology. A performance assessment is developed to compare each state and identify major policy efforts that are needed to increase the environmental and economic competitiveness of electric vehicles. A novel multi-criteria decision-support framework, integrating Life Cycle Assessment, Data Envelopment Analysis, and Agent Based Modeling, is developed. To this end, the environmental and economic impacts of battery electric vehicles are calculated based on three scenarios: an average electricity generation mix, a marginal electricity generation mix, and a solely renewable energy mix with 100% solar. The states are classified, each requiring different policy strategies, in accordance with their performance scores. The results provide important insights for advancing transportation policies and a novel framework for multi-criteria decision-making in the future analyses.

1. Introduction

Transportation sustainability has garnered tremendous interests due to the transportation sector's heavily reliance on fossil fuels (95% of the transportation sectors energy consumption in 2014 [1]) and its subsequent status as one of the largest greenhouses gas (GHG) emitters in the U.S., being responsible for 27% of U.S. energy consumption and GHG emissions in 2014 [2]. As such, the potential environmental and economic benefits electrification of the U.S. transportation sector is being extensively studied in literature [3]. Their benefits in terms of energy security and environmental impacts are highlighted in various reports [4]. However, most of efforts have myopic scope and lack of revealing the big picture in the terms of responding the changing conditions, opportunities, new insights for policy makers [5]. The efforts for widespread adoption of alternative vehicle technologies mostly failed and there is a substantial need for effective technology assessment methods to improve governments' ability to develop effective policies [6].

Comprehensive review studies by Hawkins et al. [7] and Nordelöf et al. [8] indicate that almost all of the efforts in the literature focused on GHG emissions and/or energy footprints, while few studies focuses on the water footprints of these vehicle technologies. In 2015, electricity generation from fossil fuels and nuclear energy in the U.S. required a total water withdrawal rate of 190 billion gallons of water per day, which is 39% of all freshwater withdrawals in the U.S., 71% of which are used for fossil-fuel electricity generation. Additionally, coal power plants account for nearly 52% of the total U.S. electricity generation mix, requiring 25 gallons of water withdrawal per kWh of electricity generated [9]. In addition to added water consumption and withdrawal due to rapidly increasing electricity demand, the electrification of the transportation sector has direct regional impacts on the overall water demand due to battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), which require more electricity (0.28–0.35 kWh of electricity per VMT of an average midsize EV) from the grid and might therefore increase the overall water footprint during electricity generation [10], which in turn can be a serious problem for water-scarce states such as Arizona [11]. In addition to water consumption and withdrawal rates, the CO_2 emissions and operation costs of BEVs may also vary based on the

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power source(s) used for electricity generation, infrastructure conditions, and regional energy demand profiles [12].

The majority of the studies in today's literature focus on comparing life cycle GHG emissions of BEVs, PHEVs, and internal combustion engine vehicles (ICVs), with less focus on effects of spatial and temporal variations (e.g. electricity generation mixes, driving patterns, state-specific policies, etc.) on the impacts of these vehicles [13]. To name a few studies focusing on the macro-level impacts of alternative vehicle technologies; Tamayo et al. [14] characterized regional life-cycle CO_2 emissions of BEVs and PHEVs across the North American Electric Reliability Corporation (NERC) regions in the U.S. and showed that regional variations can significantly change the CO_2 emission factors in different regions. Yuksel et al. [15] investigated the effect of regional grid mix, driving patterns, and climate on county-level carbon footprint of ICVs and PHEV. Onat et al. [16] proposed a macro level life cycle sustainability assessment framework for quantifying macro-level social, economic, and the environmental impacts (triple bottom line impacts) of alternative vehicle technologies [17]. They also proposed two assessment frameworks for determining the optimal alternative vehicle composition considering their triple bottom line impacts [18] and intuitionistic fuzzy set approach to advance the body of knowledge in existing sustainability assessment frameworks for alternative vehicle technologies [19]. While some of the referred studies achieved a great level of resolution in the terms of regions and provide important insights about the spatial and regional variations on CO_2 emissions, they do not provide a comparative framework revealing the big picture in the terms of responding the changing conditions, revealing opportunities, providing new insights for policy makers. This study contributes the body of knowledge in the sustainability assessment of alternative vehicle technologies by developing a novel integrated assessment framework in which methods of life cycle assessment, agent-based modeling, and data envelopment analysis are integrated in a systematic way. The proposed assessment framework provides a better technology assessment method to improve decision-makers' ability to develop more effective policies.

This study explores the efficiency and suitability (existing and near-future utilization potential) of BEVs in each state in the U.S. considering state-specific electricity generation mixes (and associated water withdrawals and greenhouse gas emissions), EV operation costs, and their potential market shares, which is as an outcome of the number of existing EVs, existing infrastructure, their social acceptability, and government incentives. Two important state indicators (“efficiency” and “utilization”) are introduced to explain the discrepancy between the impact (environmental and economic) reduction potential of BEVs in each state and how much of this reduction potential could/can be achieved with current government policies given the current social acceptability of BEVs. The terms “utilization” and “suitability” are complementary terms used throughout the text. Suitability is a form of estimated utilization and indicates how much of a particular state's potential (BEV's potential to mitigate environmental impacts, reduce costs in the associated state) are utilized for electrification of the light-duty transportation fleet. The term “suitability” refers to existing and/or near-future utilization potential of the associated state and these two terms are used interchangeably in accordance with the context. To estimate efficiency scores for driving BEVs, the states are benchmarked based on per-mile carbon emissions, energy consumption, water withdrawal and consumption, and operation costs. These benchmarking results are then coupled with market share estimates from the Electric Vehicle Regional Market Penetration (EVReMP) model [20], an agent based model (ABM) designed for regional assessments of electric vehicles to reveal how different states are utilizing their respective environmental impact reduction potentials. The rationale behind using agent based modeling approach is its capability to capture the macro-level consequences of micro-level interactions of agents (potential BEV buyers). The overall goal of the utilization the EVReMP model is to predict short-term adoption rates of EVs given current conditions (cost, range anxiety, availability of charging infrastructure, etc.). As the this study aims to reveal how close each state in the US comes to realizing its potential for an optimal EV fleet, the ABM serves best for this purpose by estimating short-term market shares in a systematic and scientific way. The environmental and economic impacts of electric vehicles are calculated based on three scenarios: Average electricity generation mix (Scenario 1), Marginal electricity generation mix (Scenario 2), and 100% solar charging (Scenario 3).

This study is based on outcomes of three journal papers and two doctoral dissertations, which collectively analyze the state-specific carbon/energy/water footprints, operation costs, and potential market shares of BEVs. The contribution of each thesis and papers to this work are explained in following sections of the paper. This work aims to answer following questions:

1. Which states are more environmentally and economically well suited to adopt BEVs?
2. Which states are more suitable for widespread adoption of BEVs?
3. Which states have not yet been successful enough in utilizing their reduction potentials in terms of transportation-related environmental and economic impacts? and,
4. What are the major policy areas for each state to focus on so as to more effectively utilize their potential to reduce transportation-related economic and environmental impacts?

This study reveals the big picture by showing opportunities, challenges, and present new insights for policy makers. A novel multi-criteria analysis is developed to provide a better technology assessment method to improve decision-makers' ability to develop more effective policies. In addition, policy makers can evaluate the relative performance of BEVs in certain states compared to other states that have been more successful at implementing policies aimed toward a more widespread adoption of BEVs.

2. Methods

Three major methodological approaches are utilized and integrated: Life Cycle Assessment (LCA), Data Envelop Analysis (DEA), and Agent-Based Modeling (ABM). The life cycle impacts of BEVs in each state are taken from the previous studies of the authors and the states are ranked using the DEA method, the results are then compared to the outcome of EVReMP model, an ABM estimating future market shares of EVs, to assess the efficiency versus utilization of BEVs in each state.

The operation phase of the BEVs is the most impact-intensive phase in terms of carbon, energy, and water compared to the vehicle manufacturing and end-of-life phases, and the extents of each of these impacts are highly dependent on spatial and temporal variations [16]. Hence, the impacts associated with the vehicle manufacturing and end-of-life phases are not taken into consideration. The functional unit of the assessment is per vehicle-miles traveled (VMT). In the LCA of any given vehicle, the vehicle's environmental impacts stem mainly from two life cycle phases:

Well-to-Tank (WTT), which covers upstream impacts such as those connected to the vehicle's fuel supply, and
Tank-to-Wheel (TTW), which covers tailpipe emissions and other such direct impacts incurred while driving the vehicle.