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Uncertainty-embedded dynamic life cycle sustainability assessment framework: An ex-ante perspective on the impacts of alternative vehicle options

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ABSTRACT

Alternative vehicle technologies have a great potential to minimize the transportation-related environmental impacts, reduce the reliance of the U.S. on imported petroleum, and increase energy security. However, they introduce new uncertainties related to their environmental, economic, and social impacts and certain challenges for widespread adoption. In this study, a novel method, uncertainty-embedded dynamic life cycle sustainability assessment framework, is developed to address both methodological challenges and uncertainties in transportation sustainability research. The proposed approach provides a more comprehensive, system-based sustainability assessment framework by capturing the dynamic relations among the parameters within the U.S. transportation system as a whole with respect to its environmental, social, and economic impacts. Using multivariate uncertainty analysis, likelihood of the impact reduction potentials of different vehicle types, as well as the behavioral limits of the sustainability potentials of each vehicle type are analyzed. Seven sustainability impact categories are dynamically quantified for four different vehicle types (internal combustion, hybrid, plug-in hybrid, and battery electric vehicles) from 2015 to 2050. Although impacts of electric vehicles have the largest uncertainty, they are expected (90% confidence) to be the best alternative in long-term for reducing human health impacts and air pollution from transportation. While results based on deterministic (average) values indicate that electric vehicles have greater potential of reducing greenhouse gas emissions, plug-in hybrid vehicles have the largest potential according to the results with 90% confidence interval.

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1. Introduction

Battery electric vehicles (EVs), hybrid electric vehicles (HEVs), and plug-in-hybrid electric vehicles (PHEVs) have a great potential to minimize the transportation-related environmental impacts, reduce the reliance of the U.S. on imported petroleum, and increase energy security. However, they introduce new uncertainties related to their environmental, economic, and social impacts and certain challenges for widespread adoption. While environmental assessment of these vehicles comprehensively studied in the literature [1], there are few studies presenting a complete sustainability assessment of alternative vehicle technologies. The environmental, economic, and social impacts (a.k.a. triple-bottom-line or TBL impacts) of these vehicles are crucial to truly understand the long-term sustainability of vehicles and thereby propose economically viable, socially acceptable, and environmentally friendly transportation solutions [2].

Life-cycle assessment (LCA) models have been extensively used in literature to evaluate the associated environmental impacts over the life cycles of conventional and electric vehicles [3]. LCA is a method traditionally used to quantify “cradle-to-grave” environmental impacts of products or systems [4], specifically encompassing the life cycle phases (raw material extraction and processing, transportation, use, and end-of-life) of the product/system in question [5]. A great majority of studies assessed the environmental impacts of these vehicle options without consideration of social and economic impacts at macro-level, their

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interconnections, and associated uncertainties [6]. According to comprehensive review studies about assessment of alternative vehicle technologies [1,3,6], energy consumption, greenhouse gas (GHGs) emissions, criteria air pollutants (CAPs) are the most commonly used indicators for the comparative environmental impact analyses of alternative vehicle options. To name a few, Wang et al. [7] quantified life-cycle carbon emissions, energy consumption, and particulate matter (PM2.5) emissions of alternative vehicle technologies for China. Smith [8] presented a scenario assessment for adoption of Electric Vehicles in Ireland transportation sector's Carbon Dioxide (CO_2) emissions. Li et al. [9] conducted well-to-wheel (a life cycle phase in vehicle LCA), assessment to analyze air pollution, energy consumption, and CO2 emissions from BEVs.

Although LCA-based models are used to study the energy consumption and CAP emissions of alternative vehicles, analyses of the social and economic impacts of these vehicles have gained a tremendous interest among policy-makers. For this purpose, a traditional LCA methodology should go beyond solely environmental analyses and account for the full spectrum of environmental, economic, and social impacts, collectively referred to as the triple-bottom-line (TBL) sustainability impacts [10]. To address these research needs, the life cycle sustainability assessment (LCSA) framework was introduced as a new methodological framework where three individual LCA methodologies are integrated [11]: LCA, LCC, and SLCA.

Where LCA represents the Environmental Life Cycle Assessment, LCC denotes the Life Cycle Cost analysis, and SLCA indicates the Social Life Cycle Assessment (SLCA). By considering the three pillars of sustainability in this manner (the environment, the economy, and society, respectively), the LCSA framework seeks to achieve sustainable solutions for products and/or systems in a comprehensively balanced manner [12].

Today, there is a growing collective effort among international platforms and academia to use the LCSA framework for a more informed evaluation of sustainable products, materials, and technology choices [13]. For instance, the life-cycle sustainability performances of various electricity production scenarios in the United Kingdom have been investigated based on different economic, social, and environmental indicators [14]. Yu and Halog [15] also analyzed the life-cycle sustainability impacts of solar photovoltaic development in Australia. However, only a handful of studies have used the LCSA method to evaluate the impacts of electric vehicles from a cradle-to-grave perspective. In one of these studies, Onat et al. [16] built a hybrid LCSA model using 19 macro-level sustainability indicators to analyze and compare the life cycle sustainability performances of different vehicle types (conventional gasoline, hybrid, plug-in hybrid with four different all-electric ranges, and battery-powered electric) in the United States. In another study, Onat et al. [17] presented an integrated approach in which a hybrid LCA model was combined with a LCSA approach for U.S. residential and commercial buildings. Onat et al. [18] also developed a multi-criteria decision-making model and combined it with a hybrid LCSA methodology in order to determine the optimum passenger car distribution in the U.S. Finally, to address for uncertainties related to different multi-criteria decision making for alternative vehicle options, Onat et al. [19] developed an decision making framework integrating TOPSIS and intuitionistic fuzzy set approaches for prioritize alternative vehicle options considering their life cycle sustainability impacts.

The reliability of LCA results is highly dependent on the quality of data used. According to a review of unresolved problems associated with the LCA methodology, uncertainty in life-cycle inventory data is currently among the most critical of these problems and is therefore of paramount importance [20]. The researchers also concluded that improper treatment of uncertain data could result in problematic decisions during a life cycle impact assessment and in the subsequent interpretation of LCA results. According to Finnveden [21], the quality of the input data and the degree to which uncertainties are considered are both crucial considerations in any LCA analysis. Uncertainty analyses are of particularly great importance today because the majority of LCA studies in current literature have assigned a single value to each input parameter and then developed deterministic models to estimate the environmental impacts, even though using such deterministic models fails to adequately account for the inherent variability and uncertainty in any LCA analysis. To make more informed and accurate decisions, LCA practitioners need to understand and account for the uncertainty in the input data used in LCA [22]. Several approaches have been proposed and implemented in currently available literature for conducting LCA analyses with uncertainty taken into account, including Monte Carlo simulation, which has been applied in a handful of LCA studies as a promising technique to address data uncertainty and inaccuracy [23]. According to Ciroth et al. [24], the evaluation of uncertainty is relatively new in environmental LCA, and still has not yet been sufficiently taken into account. On the other hand, the use of uncertainty analysis provides useful information to assess the reliability of LCA-based decisions and to help decision makers reduce uncertainties in LCA. To meet this need, this study used a Monte Carlo simulation technique to deal with the inherent uncertainties in the LCSA of electric vehicles.

The LCSA framework is still under development, and research efforts are still ongoing to advance the LCSA methodology for future applications [25]. According to the Coordination Action for innovation in Life Cycle Analysis for Sustainability (CALCAS) project funded by the European Commission, the current LCA methodology should be advanced in two distinct ways [26]. First, the LCSA method should be deepened by considering the dynamic relationships among the LCA parameters and by analyzing the complex causality mechanisms between system parameters. Second, the LCSA methodology must be broadened by including all three pillars of sustainable development (the environment, the economy, and society) and by extending the system boundary from the current micro-level analyses to the macro-level analyses discussed by Guinee et al. [13].

In addition to the CALCAS project, a recent review study pointed out the current potential limitations of the LCSA framework, as well as its possible future. Based on this review, the following points are highlighted with respect to the current LCSA framework [27]:

- ➢ The uncertainties in LCSA results are not yet fully addressed and discussed,
- ➢ The social LCA (S-LCA) methodology is not yet well-studied and understood,
- ➢ The current applications of the LCSA framework use a primarily mechanistic understanding, without analyzing the results of the environmental LCA, social LCA, and life cycle cost assessment simultaneously, and
- ➢ There is a lack of understanding with respect to the complex mutual interactions between the environmental, economic, and social aspects of sustainability.

In this regard, moving from the LCA method to the LCSA framework will require a system-based approach, as the LCSA methodology emphasizes the simultaneous consideration of all

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