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Life-Cycle Assessment of Electric Vehicles in the United States

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LIFE-CYCLE ASSESSMENT OF ELECTRIC VEHICLES IN THE UNITED STATES

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ABSTRACT

The U.S. Department of Energy is completing an extensive energy and environmental assessment of the life-cycle of electric vehicles. The scope of the assessment includes energy and environmental issues associated with manufacturing electric vehicles and their batteries; recycling and disposing of spent electric vehicles and vehicle batteries; operating power plants to support electric vehicle use; and the extracting the energy resource required to support the increased demand that will be placed on electric utilities when large quantities of electric vehicles penetrate U.S. markets. In addition, the assessment includes a comparable evaluation of the energy and environmental implications of the conventional vehicles.

This paper discusses the analytical framework for conducting the life-cycle assessment of electric and conventional vehicles, methodological and technological issues that are being addressed as part of the assessment, and some preliminary results.

INTRODUCTION

Because they generate no tailpipe emissions at the point of use, electric vehicles (EVs) are viewed as a critical part of air quality management strategies in urban areas plagued with "smog," the condition resulting from photochemical reactions involving air pollutants such as nitrogen oxides (NOx) and volatile organic compounds (VOCs) emitted from conventional fossil-fuel vehicles (CVs). In fact, CVs have been the target of decades of environmental regulation and in certain cities, such as Los Angeles, some fear that acceptable air quality cannot be achieved unless dramatic measures are taken to reduce their use. Significant replacement of CVs with "zero-emission" vehicles, such as EVs, has been proposed. The term "zero-emission vehicle," however, is misleading. Although EVs produce no emissions during their operation, the ancillary processes required to support EV use in society—e.g., the power generation for charging EV batteries; the fuel extraction and transport needed to support power generation; battery and vehicle manufacture, recycling, and disposal—have the potential to degrade the environment at the sites of those activities. Thus, to completely understand and analyze the energy/environmental tradeoffs between EVs and CVs, we must carefully catalog the material consumption, energy consumption, and environmental residuals for the "cradle-to-grave" life-cycle of EVs and compare it with that associated with the life-cycle for CVs. This study seeks to shed light on this issue by providing a comprehensive energy and environmental inventory of EVs and CVs.

STUDY BOUNDARIES

The scope of this study for EVs and CVs includes a quantification of the environmental residuals and energy losses over all the operational stages of the life cycle: fuel extraction and transport, processing and conversion of fuels to energy, energy distribution and end-use (see Figure 1).

The EV life cycle examined in this study includes fuel production and transport (for coal, oil, gas, uranium, hydropower, and other renewables), electricity generation, electricity transmission and distribution, battery charging, and vehicle end-use (Figure 2).

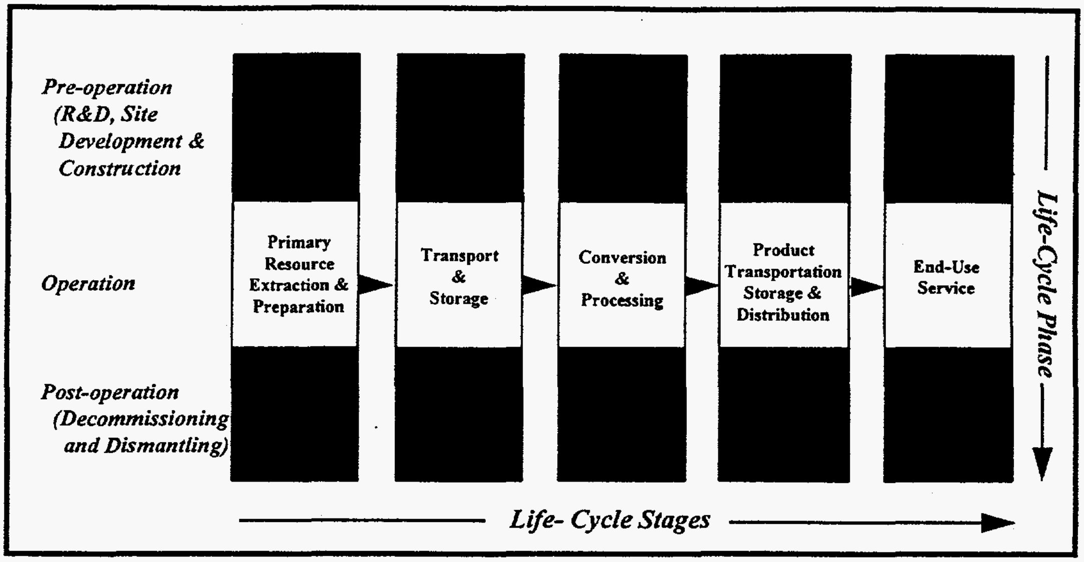

FIGURE 1. THE LIFE CYCLE STAGES AND LIFE-CYCLE PHASES

Prior environmental assessments of EVs have focused on the emissions associated with power plants and have not always examined those activities that occur upstream of the electricity generation stage. The life cycle examined for CVs includes crude oil extraction, production, and transport; oil refining; gasoline transport; vehicle fueling; and vehicle operation. Environmental assessments of CVs have typically focused on tailpipe emissions. This assessment, however, covers a significantly expanded scope. For the purposes of this study, EVs were compared with CVs using reformulated gasoline (RFG), which was considered the "benchmark" technology in this study.

Certain pre- and post-operation phases of the life-cycle stages are also being examined. For example, if utilities would need to add electricity generation capacity to meet the increased electricity demand resulting from the growing use of EVs, the EV life cycle can be viewed as responsible for the emissions resulting from the construction of that new capacity. Consequently, environmental residuals resulting from construction of the new "incremental" power plants are being included in this analysis. Key manufacturing processes which create inputs for the life-cycle are also included. For example, EV operation requires periodic replacement of the EV batteries; the manufacture of those batteries, in turn, requires inputs of particular commodities such as nickel, lead, cadmium, sodium, etc. Used batteries are either recycled or sent for disposal, also potentially affecting the environment. Such ancillary processes are being included in the inventory process when they are deemed to have the potential to be important.

STUDY SCENARIOS

Within the study boundaries described above, the assessment looks at the potential energy and environmental effects of EVs through the year 2010 by comparing a future with substantial market penetration of EVs to one without EVs. These effects are dependent on many factors, all of which are highly uncertain. In spite of the uncertainty, it is important to evaluate EV and CV vehicles in future scenarios in order to understand what factors/

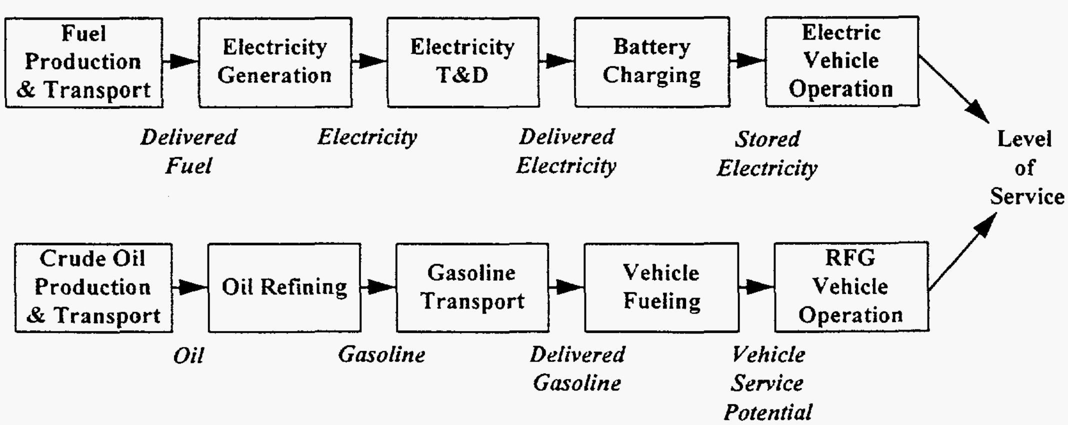

FIGURE 2. STAGES IN THE EV AND RFG CV LIFE CYCLES

uncertainties influence the energy and environmental effects of EVs and CVs. Some of these important factors include

- the level of EV penetration
- future CV fuel efficiency improvements
- the technologies employed in EVs (e.g., which battery types dominate) and the level of progress in terms of improved energy efficiency between now and the future
- the types of trips for which EVs are used
- the electric utility technologies used to provide the electricity for recharging EV batteries.

To deal with some of these factors, the study team made assumptions based on what it viewed as the likely future conditions. For example, based on a review of current battery developments, the team chose a specific mix of EV battery types to be analyzed for each of the two years included in the analysis—2000 and 2010. For other factors, the team chose to examine a range of assumptions through use of alternative scenarios of the future. For example, to assess the impact of EV penetration rates on the utility system and other effects, a case with high-EV penetration and one with more moderate EV penetration were included. In addition, we included cases that assumed EV charging would be in off-peak hours and others that assumed charging would be initiated as soon as the EVs returned "home."

Because many of the factors affecting the assessment of EVs and CVs vary from city to city, the analysis focuses on four diverse urban areas--Los Angeles, California; Houston, Texas; Washington, D.C.; and Chicago, Illinois. These areas are served by utility companies that have different power plant mixes. They have different distances associated with CV fuel transport (i.e., the distance from refining capacity to service station). In addition, they are in diverse climates (which affects the efficiency of the EVs as well as the emissions of CVs). The divergence among the cities is intended to provide a reasonable range of effects representative of those likely to occur in the United States. Results were generated for each season, allowing the effects of EVs and CVs on seasonal air quality issues to be interpreted.

STUDY APPROACH

This life-cycle assessment develops an inventory to quantify the energy and material inputs and outputs of the major processes involved in the EV and CV life cycles. It accounts for energy and material flows in and out of each of the relevant processes and quantifies the environmental residuals produced. The assessment does not translate emissions into population exposures, health and ecological impacts, and monetary damages. In the case of Los Angeles, this study was coordinated with air quality modeling work being conducted by the South Coast Air Quality Management District (SCAQMD). The study design originally called for air quality runs to be made using the results of this study, in conjunction with SCAQMD's analysis. However, the overall airborne emissions changes projected to occur in Los Angeles as a result of EV penetration levels assumed in this study were deemed to be below the threshold of sensitivity of the urban airshed model SCAQMD uses. Therefore a more complete impacts analysis that included air quality modeling was not conducted as part of this study.

The primary residuals considered in the inventory analysis are the airborne emissions: nitrogen oxides (NOx), sulfur oxides (SOx), carbon monoxide (CO), lead (Pb), particulate matter (PM-10 and total suspended particulates), carbon dioxide (CO2), methane (CH4), non-methane volatile organic compounds (NMVOCs,) and other greenhouse gases. When data were available, liquid-borne and solid residuals were also included. In addition, other pollutants are considered for certain processes. The number of processes and inputs/outputs associated with the life cycles studied in this assessment is potentially quite high. Given unlimited resources, this analysis would collect and assess data on all of the energy, material, and environmental flows and would have included every process even remotely related to the two life cycles. However, an effective (and manageable) life-cycle assessment must trade off the benefits of increased precision derived from a more comprehensive assessment versus the additional resources required to achieve that precision. Consequently, some minor process have been excluded from the study.

One feature of this study that sets it apart from most previous work on this topic is its examination of the "incremental" utility capacity that would be used to meet the extra electricity demand associated with increased use of EVs. Previous studies have tended to use "average" utility data; i.e., it is usually assumed that the additional electricity needed to charge EVs would be met by power plants that use some average national or regional fuel mix or by the current set of generating units in the region of study. The methodology for this study included a sophisticated utility dispatch modeling exercise that more closely simulates how utility companies might react to the prospects of additional EV-related demand, and how they would choose the types of plants to be brought on-line and used under the increased-demand conditions. Significant use of EVs in the future would affect load curves and could result in the addition of new capacity. Using the results of an electric utility production simulation model, this study includes projections of the ways in which the incremental demand for electricity to charge the EVs could be met, and what the environmental consequences of this added electricity demand would be.

The energy and environmental analysis of the operation of the two types of vehicles--EVs and CVs--is also being handled in this study in a great deal of detail. Driving patterns in each urban area were studied, and vehicle operating conditions were chosen to reflect the differences. Complex models were used to estimate the energy efficiency and recharging requirements of the EVs and to compute energy efficiency and emissions from conventional vehicle emissions.

Other processes involved in the life cycles (e.g., oil extraction, vehicle manufacture, steel production, etc.) were examined by gathering data from the literature; no original data were developed by measuring parameters in the field or modeling engineering aspects of specific processes.

PROJECT TEAM

This study was conducted jointly by Argonne National Laboratory (ANL), Pacific Northwest National Laboratory[(a)] (PNNL), and the National Renewable Energy Laboratory (NREL) under the direction of the Office of Energy Efficiency and Renewable Energy (EE) of the U.S. Department of Energy (DOE), with additional support from DOE's Office of Nuclear Energy.

PNNL provided an overall framework for the assessment, including specifying data requirements, and modified and applied a computerized life-cycle accounting tool to support the analysis.

NREL defined the specific scenarios to be analyzed, developed the peer-review plan (which was implemented during the course of the assessment), conducted utility dispatch modeling, conducted an analysis of environmental data for the electric utility fuel cycles involved in charging EV batteries, and interacted with the South Coast Air Quality Management District.

ANL was responsible principally for battery and electric vehicle characterization, characterization of the trips to be displaced by EVs, estimation of the total number of EVs on road, projection of EV electricity consumption, characterization of batteries, estimation of emissions from battery and vehicle manufacturing, and development of data for the benchmark RFG-fueled conventional vehicle. ANL managed the overall effort.

NATURE OF RESULTS

Based upon preliminary results, regional environmental regulators, policy makers, and utility experts can better understand such factors as

- the geographic location of positive and negative life-cycle environmental impacts likely to occur as EVs penetrate the market
- the magnitude of in-basin improvements in emission levels that could result from substantial EV market penetration
- additional electric power capacity that will be required by the year 2000 to meet the incremental electricity demand resulting from EV market penetration.

Preliminary results show

- VOC and CO emissions always appear much lower in the EVs scenarios compared with scenarios in which CVs dominate.
- NO_x and CO_2 emissions always appear lower in EV scenarios, but great variation among scenarios exists.
- Emission-constrained dispatch (to meet the requirements of Clean Air Act) reduces annual SO_2 emissions, but EV charging under such a dispatch procedure could (under some circumstances) increase the emissions of SO_2 and other pollutants.

As the assessment reaches its conclusion, additional conclusions will be available regarding

- the environmental impacts associated with a variety of EV battery technologies (including sodium-sulfur, nickel-cadmium, advanced lead-acid, and nickel-metal hydride battery manufacture and disposal) which will provide critical information to "design-for-environment" efforts related to battery development
- the best places in the life-cycle to target technological improvements if overall environmental impact is to be minimized
- what kinds of tradeoffs exist between operational strategies for supporting the EV fleet (for example, utility power plant dispatch) and resulting life-cycle environmental impacts which ideally should be minimized.

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