RECEIVED
SEP 28 1999
OSTI

**TOTAL ENERGY CYCLE ENERGY USE AND
EMISSIONS OF ELECTRIC VEHICLES**

by

Margaret K. Singh

Center for Transportation Research

Argonne National Laboratory

955 L'Enfant Plaza, SW

Suite 6000

Washington, D.C.

202-488-2440 (phone)

202-488-2413 (fax)

singhm@anl.gov

The submitted manuscript has been created by the University of Chicago as Operator of Argonne National Laboratory ("Argonne") under Contract No. W-31-109-ENG-38 with the U.S. Department of Energy. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TOTAL ENERGY CYCLE ENERGY USE AND EMISSIONS OF ELECTRIC VEHICLES

Margaret K. Singh

Center for Transportation Research, Argonne National Laboratory, 955 L'Enfant Plaza, SW,
Suite 6000, Washington, D.C.

Abstract. A total energy cycle analysis (TECA) of electric vehicles (EV) was recently completed. The EV energy cycle includes production and transport of fuels used in power plants to generate electricity, electricity generation, EV operation, and vehicle and battery manufacture. This paper summarizes the key assumptions and results of the EVTECA. The total energy requirements of EVs are estimated to be 24-35% lower than those of the conventional, gasoline-fueled vehicles they replace, while the reductions in total oil use are even greater: 55-85%. Greenhouse gases (GHG) are 24-37% lower with EVs. EVs reduce total emissions of several criteria air pollutants (VOC, CO, and NO_x) but increase total emissions of others (SO_x, TSP, and lead) over the total energy cycle. Regional emissions are generally reduced with EVs, except possibly SO_x. The limitations of the EVTECA are discussed, and its results are compared with those of other evaluations of EVs. In general, many of the results (particularly the oil use, GHG, VOC, CO, SO_x, and lead results) of the analysis are consistent with those of other evaluations.

1 INTRODUCTION

Total energy cycle assessments (TECAs) examine the energy use and environmental effects of energy systems over all the stages of an energy cycle (i.e., primary resource extraction and transport, conversion to energy products, distribution, and end use). Recently, several national laboratories completed a TECA of electric vehicles (EVs) for the U.S. Department of Energy (DOE) (1). Its purpose was to prepare an inventory of the energy use and emissions associated with EV use and compare it with a similar inventory for conventional vehicles (CVs) operating on reformulated gasoline (RFG). With this comparison, the potential contribution of EVs to reductions in oil use, greenhouse gas (GHG) emissions, and criteria air pollutants from the U.S. transportation sector could be evaluated.

In this paper, we summarize the key assumptions and inputs used in the EVTECA and its results (Sections 2-4). We discuss the limitations of the EVTECA and how these limitations affect the study's results (Section 5). Finally, we suggest what the next steps in EV energy and emissions analysis should be (Section 6).

2 EV INVENTORY

Figure 1 illustrates the EV energy cycle for which the inventory of energy use and emissions was developed. Energy use and emissions from extracting and transporting fuels used in electricity generation, the electricity generation required to charge EV batteries, and battery and vehicle manufacture are all included. Key inputs required to develop this inventory included characterization of the EVs, including their individual energy efficiencies and materials

requirements, estimates of total EV market penetration and daily usage, and an analysis of the types of fuels that would be used to provide the additional electricity required by the EVs. We discuss each of these items in Sections 2.1 to 2.3. We also describe how we allocate the EV emissions inventory to the regions in which EVs are used and outside those regions (Section 2.4).

2.1 Vehicle Characterization

Table 1 presents selected characteristics of EVs included in the EVTECA. EVs were characterized for three periods (1998-2002, 2003-2007, 2008-2010), allowing battery technology and vehicle performance to evolve over time. Table 1 includes EVs produced between 2008 and 2010. Cars and vans using four battery types were characterized: Advanced Lead-Acid (Pb-Acid), Nickel-Cadmium (Ni-Cd), Nickel-Metal Hydride (Ni-MH), and Sodium-Sulfur (Na-S).

Of the vehicle characteristics, the energy efficiency of the EVs is one of the most significant. Combined with total daily travel by EVs, EV energy efficiency determines total electricity demand by EVs. The energy efficiencies used in this analysis are based on an analysis of battery performance characteristics and, subsequently, the simulated performance of EVs with these batteries in specific driving cycles. Vans in fleet use were evaluated on the basis of the conventional urban driving cycle, while cars in household and fleet use were evaluated on the basis of a driving cycle with higher average and top speeds. The energy efficiencies presented in Table 1 are baseline efficiencies that are, in turn, affected by seasonal air conditioning and heating requirements. We accounted for the latter when examining EV use in specific metropolitan areas. In this analysis, the average energy efficiencies of EVs in operation in the

summer season in 2010 range from 0.72E6 J/km (0.32 kWh/mile) to 0.76E6 J/km (0.34 kWh/mile).

The unique material requirements of the EV batteries (and motors and controllers) and the number of battery replacements required during the life of an EV also have significant effects on the total energy use and emissions inventory of EVs. (We do not assume any preferential shift to lighter materials for the EV, as opposed to CV, body.) As Table 1 indicates, batteries make up a significant fraction (approximately 20-40%) of total EV mass. The materials used in them are not standard automobile materials (e.g., nickel) or are used in significantly greater amounts than in a CV (e.g., 284 kg of lead in the mini-compact shown in Table 1 vs. 7 kg in a comparable CV); thus, the emissions associated with producing EVs are different than those for CVs.

Further, the batteries are likely to be replaced during the life of the EVs, thereby at least doubling battery material requirements. We assumed that the Pb-Acid batteries would be replaced twice and the other three battery types once. Some of the effects of battery replacement would be reduced with the recycling of battery materials. However, given the dearth of data on the emissions generated by recycling advanced batteries, we did not account for recycling (except for the recycling of lead, for which data are available).

2.2 Market Penetration Scenarios

The energy use and emissions from EV use will vary between regions and within any region, depending on their total market penetration, daily usage, electricity demand, and the fuels used to generate the electricity required to recharge them. Thus, the EVTECA examined EV use in several metropolitan areas and under several market penetration scenarios. High and low EV

market penetration scenarios were developed for four metropolitan areas: Chicago, Houston, Los Angeles, and Washington, D.C. (hereafter referred to as Washington). This group of four areas was chosen because (a) they are among the 10 worst regions for ozone nonattainment (and thus would benefit from the fact that EVs reduce ozone precursors), (b) they are diverse with respect to their current power plant fuel mix, and (c) their climates are different.

One of the market penetration scenarios developed for each area assumes implementation of a California Zero Emission Vehicle (ZEV)-like mandate, which requires 10% of light-duty vehicles (LDVs) sold annually to be EVs, beginning in 2003. This paper focuses on presenting the results of the regional scenarios, which assume implementation of this mandate. Table 2 presents the scenarios: approximately 412,000 EVs would be in operation in Los Angeles in 2010; 265,000 in Chicago; 196,000 in Houston; and 142,000 in Washington. In each city, 56% of EVs in operation are assumed to use nickel-based batteries, 30% Na-S and 14% Pb-A.

The EVs are projected to replace CVs and their daily travel on a one-for-one, equivalent-use basis. Table 2 presents the total mileage of the EVs in the scenarios.

2.3 Utility Analysis

The fuels used to generate the electricity required to recharge EVs in each region were estimated by using a utility dispatch model. Baseline forecasts (i.e., without EV demand) of electricity demand, by season and time interval during a typical 24-hour day, and power plant capacity by fuel type were developed for each of the four regions for 2010. Given the supply forecasts, the order in which the various power plants would be used (or dispatched) to meet baseline demand was estimated with the model. Economic dispatch (least cost units first)

generally was assumed. Subsequently, for each region and each EV market penetration scenario, the electricity demand of the EV scenario was added to the baseline demand forecast, and the fuels used to meet this higher total demand (and additional capacity requirements where necessary) were estimated. Each EV is assumed to be recharged every day. The difference (or increment) in total fuel use by fuel type and total emissions generated between the baseline forecast and the forecast including EVs is assigned to EVs in the EV inventory.

Table 3 presents the baseline forecasts for each region for the summer season (three months) in 2010. Annual estimates were also developed for some EV charging scenarios, but we will focus on the summer estimates because EVs have been promoted as a technology that can reduce summertime ozone. The table clearly shows that we selected regions with different baseline fuel mixes.

Table 3 also presents our estimates of EV electricity demand under the California ZEV-like mandate. The EV demand represents from 0.4% to 1.2% additional electricity demand relative to the regions' baselines. The fuels used to provide this electricity are only presented for Houston and Washington. Similar estimates were developed as interim results for the other two regions, but they are not available. Still, the results for Houston and Washington illustrate that the fuel mix used to provide electricity for EVs will be substantially different than the average fuel mix for a region. For example, where 21% of all of Houston's electricity demand was projected to be met by coal in the baseline, when EVs are charged in the off-peak, coal is projected to provide 56% of the electricity required by EVs.

As indicated in Table 3, our analysis assumes that EVs will be recharged in each utility's off-peak hours. We believe that utilities will implement policies to encourage such charging, particularly when EV market penetration is substantial, as would be the case in the scenarios

presented in Table 2. The EVTECA report evaluated other charging scenarios, but we do not discuss them in this paper.

2.4 In- and Out-of-Basin Emissions Allocation

In-basin emissions generation is of interest as it relates to the attainment or non-attainment by metropolitan areas of the various National Ambient Air Quality Standards (NAAQS). For each region, we allocated the various components of the EV inventory to in- and out-of-basin locations. Most significant in the EV inventory is the identification of the in- and out-of-basin location of power plants providing the electricity to meet EV demand. We assume that the other components of the EV inventory (production of fuels for use in power plants and vehicle and battery manufacture) will occur outside the region.

3 CV INVENTORY

Figure 1 also illustrates the CV energy cycle for which an inventory of energy use and emissions was developed. Energy use and emissions associated with producing and transporting crude oil and reformulated gasoline (RFG), vehicle manufacture, and vehicle operation are all included. The weights and baseline fuel economies of the CVs that would be replaced by EVs are presented in Table 1. As with the EVs, seasonal adjustments are made to account for air conditioning and heating requirements in the different metropolitan areas analyzed. The weighted average fuel economy of the CVs in the scenarios in 2010 is approximately 0.11 L/km (21 mpg). The CV operating emissions are estimated by using EPA's MOBILE5a model. The CVs are

assumed to use RFG oxygenated with methyl tertiary butyl ether (MTBE) in Los Angeles, Washington, and Houston and with ethanol in Chicago.

As with EVs, we estimated which components of the CV emissions occurred within a region and which outside. We assumed that all CV vehicle operation replaced by EVs would be in-basin. We also reviewed crude refining capacity and oxygenate production capacity for each region and evaluated the likelihood of in-basin RFG production. We determined that in-basin refining of RFG is likely in all the regions except Washington, while oxygenate production would only occur in Houston. Vehicle manufacture is assumed to occur out-of-basin.

4 TOTAL ENERGY CYCLE RESULTS

While the EVTECA report includes selected information about all four metropolitan areas, we only generated total EV and CV inventories for Houston and Washington in 2010. Thus, we will focus on results for these two regions in the remainder of the paper.

Before reporting the results, several clarifications are necessary. First, the results presented for CVs in a region are just the energy use and emissions that would be required and/or generated by the CVs that the EVs would replace. The CV results are not results for the full fleet of CVs in that region.

Second, the total energy use and emissions associated with each vehicle's production, including battery replacement, were allocated over the life of the vehicle on a per mile of travel basis. The vehicle manufacturing results for 2010 are based on (a) these vehicle-specific per-mile energy use and emissions estimates and (b) the number of miles driven in 2010 by each specific EV and CV type.

Third, the results presented below include a category called "Ancillary Energy." It is not a separate energy cycle stage. Ancillary energy is the energy required to produce and deliver electricity (and, to a lesser extent, other fuels) used in miscellaneous processes within the energy cycles. The emissions associated with all of the various uses of ancillary energy are grouped together. They are all assumed to occur outside the regions studied.

Finally, in the EVTECA report, we present total energy cycle results for two off-peak scenarios for each region. We only present the results here for the scenarios termed "off-peak combined cycle": the results of the other scenarios are quite similar.

4.1 Energy Use Results

Table 4 presents the total energy resource consumption of the EV and CV energy cycles for EVs and CVs operating in Houston and Washington in 2010. The results are presented on a per-mile basis, although total energy resource requirements for total EV travel and travel by a comparable number of CVs were also estimated.

The two CV energy cycles show very similar levels of total energy consumption per vehicle mile traveled: approximately $4.5\text{E}6$ - $4.6\text{E}6$ J/km (6800-7000 Btu/mile). Of the CV total energy consumption, 80% is in vehicle operation.

The total energy requirements of the EV energy cycles ranges from $3.0\text{E}6$ to $3.3\text{E}6$ J/km (4600-5100 Btu/mile). A good part of the reason that EVs in Houston require more total energy than those in Washington is *not* that the EVs in Houston are less energy efficient, but that the average conversion efficiencies for the power plants used to provide electricity for EVs in Houston are lower than those for the plants serving Washington's EV demand.

Over the total energy cycle, EV energy requirements are 24% to 35% lower than those of CVs. The reductions in total oil use requirements are even greater: over 85% in Houston and 55% in Washington. The reduction is lower in Washington because, as we saw in Table 3, fuel oil is projected to provide nearly 50% of the area's electricity for EVs, while oil-fueled power plants are not projected to be a source of electricity for EVs in Houston.

4.2 Environmental Results

Tables 5 and 6 present the environmental results for EVs and CVs in Houston and Washington. Emissions of carbon dioxide (CO₂), methane (CH₄), volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NO_x), total suspended particulates (TSP), sulfur oxides (SO_x), and lead (Pb) are presented. The totals are disaggregated by energy cycle stage. We also show the in-basin totals for selected pollutants.

In general, from a total energy cycle perspective, use of EVs to replace CVs are projected in this study to benefit the environment in the following ways:

- **CO₂:** EVs reduce total CO₂ emissions. The reductions shown here range from 25% to 38%.
(When combined with the CH₄ results discussed below, EVs reduce CO₂-equivalent GHG emissions by 24% to 37%.)
- **VOC:** VOC emissions are dramatically reduced by EVs. Total VOC reductions are 91%, and in-basin reductions are 99% for both regions.
- **CO:** CO emissions are also dramatically reduced by EVs. Total CO is reduced from 83% to 85%. In-basin CO emissions are reduced from 97% to nearly 100%.

- **NO_x:** Both EV scenarios lead to NO_x reductions, both total and in-basin. However, the results show that the level of reduction can vary greatly. For Houston, total NO_x is reduced 7%, while for Washington, NO_x is reduced 32%. In Houston, the in-basin NO_x reductions are 25%, while in Washington, the in-basin reductions are 91%. All the power plants providing electricity for EVs are located within the Houston region, while most of the electricity generated for EVs operating in Washington is generated outside the region.

On the other hand, some increases in emissions might result from the replacement of CVs with EVs. The results showed the following:

- **CH₄:** EVs will likely lead to CH₄ increases because more CH₄ is generated in the production of fuels for the power plants than in the production of fuels used in CV operation. The total EV energy cycle for Houston shows a 10% increase in CH₄, and other scenario results not presented in this paper generally indicate CH₄ increases. However, CH₄ will not always increase, as indicated by the Washington results.
- **TSP:** TSP emissions will increase with EVs due to vehicle and battery manufacture and, in some instances, power plant operations. The increases shown here range from 19% to 76%. However, in-basin TSP emissions are generally lower with EVs. In-basin reductions of 31% to 74% were estimated. We do not have the data to present particulate matter (PM) results by size of particles (e.g., PM with diameter smaller than 10 μm [PM-10]).
- **SO_x:** SO_x emissions are 10 times higher in the EV scenarios. The major source of the emissions is not power production, but battery manufacturing (particularly the nickel batteries). The in-basin SO_x emissions with EVs are 5 times higher than with CVs in Houston, but in Washington, they are essentially the same.

- **Pb:** Lead emissions increase approximately 400-500% because of the use of Pb-Acid batteries in some of the EVs, and because EVs use more copper (the production of copper generates lead emissions). All of these emissions are assumed to be out-of-basin in this analysis, although we anticipate that some recycling of battery materials may occur in-basin.

Tables 5 and 6 also illustrate that the relative importance of each stage of the energy cycle to the total emissions of EVs and CVs varies between the two vehicle types and depends on which pollutant is being evaluated.

5 DISCUSSION

The results reported above are obviously only as good as the data used to develop them and the methodology applied to analyze them. In this section, we will discuss the limitations of both the data and methodology used in the EVTECA and the confidence we have in the direction of our results.

5.1 Vehicle Characterization

The EV and CV characterizations were generally completed by early 1995. EV technology is evolving rapidly. Today, we would not include the Ni-Cd or Na-S batteries because EV manufacturers no longer consider them major battery candidates. Instead, we would probably include lithium batteries. Since nickel production contributed significantly to the EV SO_x totals, dropping the Ni-Cd batteries could reduce the SO_x emissions associated with EVs, but only if they were completely replaced by another type of battery not requiring nickel.

Also, today we would include electric light-trucks, which are lighter than vans, and would therefore require less electricity to operate. Total EV electricity demand for the same number of EVs would thus be lower than we have estimated. However, the fuel demand of the CVs would also be lower if we replaced conventional vans with conventional light-trucks, so the relative energy use of EVs and CVs might still be quite similar if that were the only change.

The CV characterization might also be considered dated. The CVs characterized here achieve an average of 0.11 L/km in urban driving in 2010. Some might argue that that fuel economy estimate should now be higher. Higher fuel economy would reduce the CVs total energy use, oil use, and CO₂ emissions. Certainly today we would revise the characterization to take account of the National Low Emission Vehicle (NLEV) standards now being implemented. The CVs in this study meet the less stringent Tier I standards (less stringent for NO_x and VOC-like emissions).

5.2 Utility Analysis

The utility analysis also was largely completed by early 1995, so it preceded current initiatives to deregulate the utility industry. With deregulation, the power plants of a region's local utility will not necessarily be the units used to provide the electricity used to charge EVs, which is what we assumed in this analysis. If we were to conduct the utility analysis now and assume deregulation, the fuel mixes projected to be used in recharging EVs would likely be different than what we have analyzed here.

Projecting which power plants are likely to be dispatched to meet EV demand, particularly in an era of deregulation, is very difficult. Some guidelines need to be developed for such projections. We believe that the ideal approach, which is used in the EVTECA and reported in

this paper, is an incremental analysis: project which power plants will be used in the off-peak hours assuming no EV penetration and compare them with those that would be dispatched with EV penetration. However, for low levels of EV market penetration (i.e., well below ZEV mandate-like numbers), it is not worth the effort to do so: projections of the average power plant fuel mix might be used in such circumstances.

Even for significant EV market penetration, substantial effort to project with the specificity we attempted in this analysis may not be worth the effort, particularly given the fact that with deregulation, fuels could come from many different utilities. So, an alternative approach might be to analyze the implications of several mixes of fuels to see what the various effects of those fuel mixes would be. Ideally, one would try to focus on which power plants in a region are considered baseline plants and therefore already used to meet other off-peak demands and thus not available for additional off-peak use. One can get a sense of the implications of using such an approach by examining the Houston and Washington results presented in this paper — for both regions, about 45% of the fuel used to charge EVs is estimated to be natural gas. However, the rest of Houston's electricity is derived from coal power plants, and 49% of the fuel used in Washington is oil. In spite of this difference, the energy cycle results for each region are quite similar, at least in direction of the results.

5.3 Vehicle and Battery Manufacturing Analysis

For vehicles with unique materials, such as battery materials, it is important to analyze the effects of manufacturing those materials. Our estimates of the SO_x generated when producing nickel for use in EV batteries had a large impact on the SO_x results of this analysis. (See Table 7

for the SO_x emission rates we estimated for the production of various vehicle materials and batteries: nickel has the highest rate by far.) The materials analysis presented here demonstrates that simply comparing the CV vehicle operation emissions to the EV power plant emissions, as many past EV studies have done, could lead to incorrect conclusions about the relative emissions changes achieved with EVs.

At the same time, our vehicle and battery manufacturing emissions results cannot be regarded as "final." It is likely that, with significant market penetration of EVs and the need to replace batteries during the life of an EV, advanced battery materials will be recycled. Our analysis only included recycling of lead, and even for that we just assume historic recycling rates. Battery recycling will reduce the process emissions associated with the virgin material production. Thus, for example, the SO_x emissions that we project for the production of an average nickel-based battery will be significantly reduced.

There are two other limitations to the manufacturing analysis we conducted in the EVTECA. First, not all the battery materials were characterized (though the major materials were), and those that were characterized were not always completely characterized. Second, while criteria air pollutants were estimated, the increased production of heavy metals and other air and water emissions and solid waste from battery production were not comprehensively addressed. It can be anticipated that such pollutants will increase, especially in areas where raw battery materials are extracted and batteries are subsequently produced and recycled. Future analyses should examine these pollutants.

5.4 Regional Inventories

We only completed inventories for the use of EVs in Houston and Washington. Because of funding constraints, we were not able to complete such inventories for Chicago or Los Angeles. We have estimated separately that, of all four regions, EVs operating in Chicago generally have the highest rate of CO₂, TSP, and NO_x emissions from power plants (this under a dispatch order designed to control SO_x). We do not know if such power plant results would affect the total energy cycle results for EVs in Chicago so much that their relationship to the CV results would be different than those for Houston and Washington.

5.5 Emissions Results

The limitations described above clearly could affect the specific estimates that we developed in the EVTECA if addressed by further analysis. Nevertheless, we do not believe that they would change the overall direction of the results. We base this conclusion in part on a review of the results of other evaluations of the environmental impacts of EVs (2-5). Our results (particularly the oil use, GHG, VOC, CO, SO_x, and Pb results) are generally consistent with those of these references, in spite of the fact that the studies all contain different assumptions regarding EV efficiency, power plant mix, and CV fuel economy. Because of page limitations, we cannot present a detailed evaluation of the EVTECA results versus those of these studies, but interested readers might wish to review these references.

At the same time that we acknowledge that our specific emissions estimates could change, we do not want to ignore the fact that such estimates should also be evaluated in the context of the

potential overall impact of EVs on a region's total inventory of pollutants. To provide some perspective on this potential impact of EVs, we examined the effect of EV-related VOC reductions on VOC inventories in Houston and Washington. (But we can not estimate the effect of EVs on peak ozone levels.) VOC inventories for 1990 for these regions are available in EPA-required State Implementation Plan documents; no estimates for 2010 are available (6-7). Table 8 presents these inventories and the in-basin VOC emissions reductions achieved with EVs in 2010 as estimated in the EVTECA. The results indicate that, if 2010 regional VOC inventory were the same as in 1990, a California ZEV-like mandate, as is assumed in our market penetration scenarios, might eliminate 1-3% of the mobile-source VOC emissions in these two regions, but less than 1% of the total man-made VOC emissions. Not surprisingly, EVs would have to be just one of many strategies implemented to help reduce ozone precursors.

6 CONCLUSION

In sum, the EVTECA analysis indicates that, over the entire energy cycle, EVs will reduce total energy and oil use and GHG, VOC, CO, and NO_x emissions, but will increase SO_x, TSP, and Pb emissions. The key determinants of these results are the EV and CV energy efficiencies and power plant fuel mixes that we estimated. Other factors, such as the level of battery recycling assumed, affect the specific numerical results, but are not key to the overall direction of the results. Our results (particularly the oil use, GHG, VOC, CO, SO_x, and Pb results) are generally consistent with those of other evaluations of EVs.

We recommend that some additional analysis of the energy and environmental implications of EVs be undertaken. The following research is needed:

1. The emissions associated with the production of various batteries should be examined in more detail. As indicated previously, while criteria air pollutants were estimated in the EVTECA, the increased production of heavy metals and other air and water emissions and solid waste from battery production were not comprehensively addressed. They should be. Also, the emissions from recycling advanced batteries, especially nickel-based batteries, need to be characterized. An evaluation of the potential environmental impacts of increased battery production and recycling on locations in which batteries are produced and recycled is also needed.
2. Our characterization of particulate emissions was particularly weak. PM-10 and PM-2.5 estimates for the entire EV lifecycle are needed.
3. The impact of the changes in the pollutant burden associated with a ZEV-like mandate on a metropolitan region's pollutant burden needs to be more thoroughly evaluated. The limited analysis presented in this paper suggests it is small.

We also recommend that a more flexible energy cycle tool than the one used in the EVTECA be developed. The EVTECA results were "dated" before they were released. In an era of rapidly evolving technology and one in which there are widely different opinions about the future characteristics of that technology, a model that would allow us to quickly examine the implications of different power plant fuel mixes and technologies, battery types, and even alternative characterizations of the baseline CV would be very useful.

Finally, where EVs fit relative to other technologies and policies in meeting (a) national goals to reduce oil use and GHG emissions, while also meeting emission standards, and (b) national and regional goals to reduce criteria pollutants cannot be fully evaluated unless the cost of EV

manufacture and use is estimated. It was not the focus of this project to examine lifecycle costs, but we recommend that future analyses of EV emissions include such cost analysis.

7 ACKNOWLEDGMENTS

The author thanks the many persons who worked on the EVTECA at Argonne National Laboratory, National Renewables Energy Laboratory, and Pacific Northwest National Laboratory and the U.S. Department of Energy staff who provided funding and guidance for this project. But, in particular, the author would like to single out for thanks Karen Andreozzi, formerly of U.S. DOE, and Phil Patterson, still with U.S. DOE, for their continued and enthusiastic support during the several years that the EVTECA was conducted. Work sponsored by the U.S. Department of Energy, The Office of Transportation Technologies, under Contract W-31-109-Eng-38.

8 REFERENCES

1. Singh, M., et al, *Total Energy Cycle Assessment of Electric and Conventional Vehicles: An Energy and Environmental Analysis*, Vols. 1-4, ANL/ES/RP-96387 (January 1998).
2. Delucchi, M., *A Revised Model of Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity* (Draft), Institute of Transportation Studies (November 1997).
3. Wang, M., unpublished information (April 1998).
4. DeWulf, C., Ohio EPA, *Transportation 2010* (November 7, 1997).

5. *Utility Emissions Associated with Electric and Hybrid Vehicle Charging: Interim Report*, DOE/CE-0395 (April 1993).
6. *Estimates Towards 15% ROP, SIP- Houston/Galveston (3/15/96)*, provided by U.S. EPA (April 1996).
7. *Final State Implementation Plan Revision to Achieve a Fifteen Percent Reduction in Volatile Organic Compound Emissions for the Washington DC-MD-VA Nonattainment Area*, prepared by the Metropolitan Washington Council of Governments (January 1994).

LIST OF TABLES

TABLE 1 Vehicle Characteristics: EVs and CVs Produced in 2008-2010^a

TABLE 2 EVs in Operation in 2010, by Region, in Scenario Assuming Implementation of California ZEV-Like Mandate (000)

TABLE 3 Electricity Demand Estimates by Region and System Energy by Fuel Type, Summer 2010

TABLE 4 Total Energy Resource Use by EVs and CVs in 2010 (Btu/mi)

TABLE 5 Energy Cycle Emissions for EVs Operating in Houston, Summer 2010 (tons)

TABLE 6 Energy Cycle Emissions for EVs Operating in Washington, D.C., Summer 2010 (tons)

TABLE 7 Emissions SO_x/Material

or Product (lb SO_x/ton of product)

TABLE 8 EV In-Basin VOC Reductions in 2010 Compared with In-Basin VOC Inventories in 1990 (tons/day)

LIST OF FIGURES

FIGURE 1 Stages in the EV and CV Energy Cycles

TABLE 1 Vehicle Characteristics: EVs and CVs Produced in 2008-2010 ^a

Vehicle Type	Battery Type	Battery Weight (lb)	Curb Weight without Battery ^b (lb)	Range to 80% DOD ^c (mi)	Acceleration (0-60 mph) at 80% DOD (s)	Base Energy Efficiency at Wall Outlet (kWh/mi)	Base Fuel Economy (mpg)
Mini-Compact							
CV	NA ^d	NA	2139	NA	NA	NA	36.4
EV	Pb-Acid	904	1711	100	10.0	0.209	NA
Compact							
CV	NA	NA	2543	NA	NA	NA	29.1
EV	Na-S	803	2034	154	12.0	0.208	NA
EV	Ni-Cd	1336	2034	150	7.3	0.248	NA
EV	Ni-MH	873	2034	150	8.0	0.241	NA
Minivan							
CV	NA	NA	2980	NA	NA	NA	23.2
EV	Na-S	811	2384	139	15.0	0.232	NA
EV	Ni-Cd	1127	2384	120	10.0	0.261	NA
EV	Ni-MH	761	2384	120	11.0	0.262	NA
Full-Size Van							
CV	NA	NA	5278	NA	NA	NA	14.8
EV	Na-S	1372	4230	144	15.0	0.379	NA
EV	Ni-Cd	1828	4230	120	10.2	0.424	NA
EV	Ni-MH	1235	4230	120	11.4	0.426	NA

^a Cars are evaluated on the LA-92 driving cycle and vans on FUDS (Federal Urban Driving Schedule).

^b Battery is included in CV curb weight.

^c DOD = Depth of discharge.

^d NA = Not applicable.

Note: 1 lb = 0.454 kg; 1 mi = 1.61 km; 1 mpg = 0.43 km/L.

TABLE 2 EVs in Operation in 2010, by Region, in Scenario Assuming Implementation of California ZEV-Like Mandate (000)

Battery Type	Region			
	Chicago	Houston	Los Angeles	Washington
<i>Vans</i>				
Pb-Acid	3.0	2.2	4.6	1.6
Na-S	22.7	16.8	35.4	12.2
Ni-Cd	15.8	11.7	24.6	8.5
Ni-MH	15.8	11.7	24.6	8.5
Total Vans	57.3	42.3	89.3	30.8
<i>Cars</i>				
Pb-Acid	34.6	25.5	54.0	18.6
Na-S	57.6	42.6	89.8	31.0
Ni-Cd	57.6	42.6	89.8	31.0
Ni-MH	57.6	42.6	89.8	31.0
Total Cars	207.4	153.3	323.2	111.6
Total Vehicles	264.7	195.6	412.5	142.4
Annual Mileage (10e6)	3252	2571	5572	1724
Summer Mileage (10e6)	890	704	1526	472

Note: 1 mi = 1.61 km.

TABLE 3 Electricity Demand Estimates by Region and System Energy by Fuel Type, Summer 2010

Region	Electricity Demand (10e3 MWh)	System Energy Required (%), by Fuel Type					
		Coal	Natural Gas	Nuclear	Oil	Other	Imports
Chicago							
Baseline	30,325	30.6	1.9	67.5	-	-	-
Off-Peak Charging of EVs	304	NA	NA	NA	NA	NA	-
Houston							
Baseline	25,193	20.6	74.2	5.2	-	-	-
Off-Peak Charging of EVs	248	56.0	44.0	-	-	-	-
Los Angeles							
Baseline	42,381	13.4	59.4	12.0	-	11.1	4.1
Off-Peak Charging of EVs	522	NA	NA	NA	NA	NA	-
Washington							
Baseline	40,201	55.1	17.4	16.7	9.3	1.5	-
Off-Peak Charging of EVs	169	3.8	46.9	-	49.3	-	-

NA = not available.

TABLE 4 Total Energy Resource Use by EVs and CVs in 2010 (Btu/mi)

Energy Cycle Stage	Houston			Washington		
	CV	EV	Reduction with EVs (%)	CV	EV	Reduction with EVs (%)
RFG Use	5413			5627		
Electricity Delivered to Vehicle ^a		1146			1167	
Fuel Input to Power Plants		3663			3171	
Other Fuel Extraction, Processing and Transportation	585	284		608	327	
Vehicle and Battery Production	285	343		297	342	
Ancillary Energy	467	840		470	736	
Total	6750	5131	24	7002	4575	35
Oil	5049	687	86	5234	2349	55
Gas	1409	2100	-49	1464	1813	-24
Coal	292	2344	-703	304	412	-36

^a Also included in Fuel Input to Power Plants.

Note: 1 mi = 1.61 km; 1 Btu = 1.055×10^3 Joules.

TABLE 5 Energy Cycle Emissions for EVs Operating in Houston, Summer 2010 (tons)

Source	Share of Emissions, by Vehicle Type		Reduction with EVs (%)	Share of Emissions, by Vehicle Type		Reduction with EVs (%)
	CVs	EVs		CVs	EVs	
	<i>CO₂</i>			<i>CH₄</i>		
TOTAL (tons)	381,934	286,010	25.1	617	681	-10.3
SHARE:						
CV/Power Plant Operation	0.786	0.754		0.056	0.011	
Fuel Production	0.108	0.036		0.437	0.828	
Vehicle Manufacture	0.063	0.165		0.003	0.004	
Ancillary Energy	0.042	0.045		0.505	0.157	
	<i>TSP</i>			<i>SO_x</i>		
TOTAL (tons)	65	77	-18.6	273	2,957	-984.3
SHARE:						
CV/Power Plant Operation	0.215	0.055		0.125	0.178	
Fuel Production	0.061	0.070		0.210	0.007	
Vehicle Manufacture	0.669	0.838		0.511	0.805	
Ancillary Energy	0.056	0.037		0.154	0.010	
<i>In-Basin</i>	0.252	0.055	74.3	0.295	0.178	-554.0
	<i>NO_x</i>			<i>VOC</i>		
TOTAL (tons)	750	694	7.4	509	47	90.7
SHARE:						
CV/Power Plant Operation	0.597	0.592		0.926	0.109	
Fuel Production	0.206	0.232		0.030	0.668	
Vehicle Manufacture	0.043	0.099		0.006	0.097	
Ancillary Energy	0.153	0.076		0.038	0.126	
<i>In-Basin</i>	0.732	0.592	25.1	0.937	0.109	98.9
	<i>CO</i>			<i>Pb</i>		
TOTAL (tons)	3,915	677	82.7	0.020	0.12	-500.0
SHARE:						
CV/Power Plant Operation	0.888	0.162		0.000	0.000	
Fuel Production	0.007	0.053		0.000	0.000	
Vehicle Manufacture	0.100	0.772		1.000	1.000	
Ancillary Energy	0.005	0.012		0.000	0.000	
<i>In-Basin</i>	0.892	0.162	96.8			

Note: 1 ton = 0.907 Mg.

TABLE 6 Energy Cycle Emissions for EVs Operating in Washington, D.C., Summer 2010 (tons)

	Share of Emissions, by Vehicle Type		Reduction with EVs (%)	Share of Emissions, by Vehicle Type		Reduction with EVs (%)
	CVs	EVs		CVs	EVs	
	<i>CO₂</i>			<i>CH₄</i>		
TOTAL (tons)	266,804	166,081	37.8	427	408	4.6
SHARE:						
CV/Power Plant Operation	0.785	0.692		0.050	0.013	
Fuel Production	0.109	0.072		0.440	0.735	
Vehicle Manufacture	0.063	0.187		0.003	0.005	
Ancillary Energy	0.042	0.049		0.507	0.247	
	<i>TSP</i>			<i>SO_x</i>		
TOTAL (tons)	45	79	-75.9	192	2,073	-982.6
SHARE:						
CV/Power Plant Operation	0.209	0.420		0.124	0.238	
Fuel Production	0.063	0.015		0.219	0.009	
Vehicle Manufacture	0.672	0.542		0.504	0.743	
Ancillary Energy	0.057	0.023		0.153	0.009	
<i>In-Basin</i>	0.209	0.081	31.4	0.124	0.011	2.7
	<i>NO_x</i>			<i>VOC</i>		
TOTAL (tons)	517	353	31.7	321	29	91.0
SHARE:						
CV/Power Plant Operation	0.594	0.519		0.920	0.178	
Fuel Production	0.208	0.261		0.031	0.588	
Vehicle Manufacture	0.043	0.128		0.007	0.106	
Ancillary Energy	0.155	0.092		0.042	0.128	
<i>In-Basin</i>	0.594	0.079	90.9	0.920	0.067	99.3
	<i>CO</i>			<i>Pb</i>		
TOTAL (tons)	2,613	393	84.9	0.017	0.09	-403.5
SHARE:						
CV/Power Plant Operation	0.884	0.059		0.000	0.000	
Fuel Production	0.006	0.044		0.000	0.000	
Vehicle Manufacture	0.105	0.884		1.000	1.000	
Ancillary Energy	0.005	0.013		0.000	0.000	
<i>In-Basin</i>	0.884	0.019	99.7			

Note: 1 ton = 0.907 Mg.

**TABLE 7 Emissions SO_x/Material
or Product (lb SO_x/ton of product)**

Material or Product	SO _x
<i>Materials</i>	
Steel Parts	14.2
Iron Castings	38.8
Aluminum Parts	71.1
Plastics	45.0
Lead	16.9
Nickel	3284.0
<i>Battery</i>	
Pb-Acid	12.3
Na-S	45.4
Ni-Cd	1274.0
Ni-MH	948.0

Note: 1 ton = 0.907 Mg.

TABLE 8 EV In-Basin VOC Reductions in 2010 Compared with In-Basin VOC Inventories in 1990 (tons/day)

Region/Man-Made VOC by Source Type	1990 VOC Inventory	2010 EV VOC Reduction (summer day)	EV VOC Reduction as a % of Inventory
<i>Houston</i>			
On-Road Mobile	163.4	5.11	3.1
All Other	813.4	0.05	0.01
Total	976.8	5.16	0.5
<i>Washington</i>			
On-Road Mobile	252.5	3.21	1.3
All Other	286.1	0	0
Total	538.6	3.21	0.6

Note: 1 ton = 0.907 Mg.

Margaret K. Singh

FIGURE 1 Stages in the EV and CV Energy Cycles

FIGURE 1 Stages in the EV and CV Energy Cycles

Unlabeled
in 1990s
figure