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**Total Energy Cycle Assessment
Of Electric and Conventional Vehicles:
An Energy and Environmental Analysis**

Volume I:
Technical Report

Prepared by
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The Total Energy Cycle Assessment of Electric and Conventional Vehicles: An Energy and Environmental Analysis is a four volume report. *Volume I: Technical Report* contains the major results, a discussion of the conceptual framework of the study, and summaries of the vehicle, utility, fuel production, and manufacturing analyses. It also contains summaries of comments provided by external peer reviewers and brief responses to these comments. *Volume II: Appendices A-D to Technical Report* contains additional details on the vehicle, utility, and materials analyses and discusses several details of the methodology. *Volume III: Appendix E to Technical Report, Comprehensive EVTECA Results Tables* presents the results of the total energy cycle model runs, which are summarized in Volume I. *Volume IV: Peer Review Comments on Technical Report* includes copies of all the external peer review comments on the report distributed for review in July 1997.

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PREAMBLE

This report compares the energy use, oil use and emissions of electric vehicles (EVs) with those of conventional, gasoline-powered vehicles (CVs) over the total life cycle of the vehicles. The various stages included in the vehicles' life cycles include vehicle manufacture, fuel production, and vehicle operation. Disposal is not included. An inventory of the air emissions associated with each stage of the life cycle is estimated. Water pollutants and solid wastes are reported for individual processes, but no comprehensive inventory is developed. While the report documents changes in air emissions associated with EV operation as opposed to CV use, it does not address the impacts of those changes (such as air quality and/or human exposure), except very briefly.

Because of rapid changes in the development of EVs and utility deregulation, the report is dated. It reflects EV and utility characterizations made in the 1993 to 1995 time frame. However, we believe it contains useful information upon which to build future evaluations of EVs. Thus rather than updating and revising the report, the report is being made available to interested parties, along with the peer-review comments on it. DOE plans to build on the information gathered in this assessment to develop a more flexible tool to model the energy cycle emissions of EVs, one which will be easier to keep up-to-date. (The model will be designed to allow users to input some of their own assumptions regarding EV use: e.g., battery type mix, number of battery replacements, vehicle energy efficiency, daily EV use, and power plant fuel mix.) Potential users of this report should regard it similarly: i.e., as a report to build on, not as one which claims to definitively answer questions about the environmental impact of EVs.

Summary of Key Comments by Reviewers and Response by Analytical Team

This draft report (Volumes I-III) was sent out for peer review in July 1997. We received extensive comments from 10 organizations and individuals. The *reviewers* include the following:

Mr. Jeff Trask
American Petroleum Institute (API)

Ms. Marijke Bekken
California Air Resources Board (CARB)

Ms. Susan Willis
Manager, Fuels Studies & Standards Group,
Mobile Source Division
US EPA (EPA)

Mr. Ed Ridell
Manager, Electric Transportation
Electric Power Research Institute (EPRI)

Mr. Robert Hayden
Executive Director
Electric Vehicle Association of the Americas (EVAA)

Mr. David Goldstein
President
and
Mr. Morris Altschuler
Environmental Chairman
Electric Vehicle Association of Greater Washington (EVA/DC)

Ms. Sheral Arbuckle
Ford AFVC (Ford)

Mr. Brian Harney
Manager, Policy and Issues Management
Mobil Oil Corporation (Mobil Oil)

Mr. Thomas Hickman
Idaho National Engineering Laboratory (INEL)

Dr. Paul Butler
Manager, Energy Storage System,
Analysis and Development,
Sandia National Laboratories (Sandia)

Ms. Aeron Arlin
Western States Petroleum Association (WSPA)

The EPRI and EVAA reviews are combined in one review. Marijke Bekken and Sue Willis specifically indicated that their reviews do not (necessarily) represent their respective organizations' "official" review. Bekken requested that we make it clear that her comments are her personal comments and so we refer to her comments below as "Bekken of CARB". WSPA commissioned a review by Sierra Research which both WSPA and API submitted and endorsed with their comments. Comments by Sierra Research are thus also included.

What we consider to be the key comments are summarized below as are our responses to those comments. *Key comments* were made on the EV characterization, CV characterization, scenarios, utility dispatch, materials analysis, results, as well as other topics and the study as a whole. In Volume IV of this report, we have included copies of all the comments which we were given permission to reproduce. We encourage the reader to review those comments, since it is clear that a great deal of effort went into all of the reviews and since in this brief summary we may not have included comments which some reviewers think are critical.

Rather than revising the report to address these comments specifically, DOE decided to release the report as is, with the comments included, and then build on the results of this study. Thus, the *responses to comments* which are provided below reflect no additional analysis.

C. 1 EV Characterization: Key Comments

C.1.1 Battery characterization

Several reviewers indicated that the battery characterization is dated and/or inaccurate (EPRI/EVAA, EVA/DC, Ford, INEL, Sandia). In particular, the inclusion of the Na-S batteries is questioned (EPRI/EVAA, EVA/DC, INEL, Sandia) as is the exclusion of lithium batteries (EPRI/EVAA, Sandia). Some think the Ni-Cd batteries are also unlikely to be commercialized (EPRI/EVAA, EVA/DC, INEL). EPRI/EVAA state that the Ni-MH batteries should be assumed to penetrate earlier than is assumed in the scenarios (specifically EPRI/EVAA believes they will be used in EVs prior to 2003). EPRI/EVAA states that the battery performance characteristics are out-of-date and the use of this old data leads to a completely flawed analysis of EVs.

A number of reviewers question the battery replacement assumptions. EPRI/EVAA and EVA/DC state that the Pb-acid batteries will be replaced once, not twice, and the Ni-MH batteries may last the life of the vehicle, rather than requiring one replacement. On the other hand, API, Ford, and Mobil Oil state that the batteries will be replaced more often than is assumed in the report, especially the Pb-acid batteries (according to Ford).

C.1.2 Vehicle characterization

Two reviewers (EPRI/EVAA, EVA/DC) believe that the EVs characterized are based on out-of-date prototypes. Use of out-of-date prototypes in particular affects the estimates of EV energy efficiency used in the report. In particular, there is an overemphasis on electric vans. Both EPRI/EVAA and Ford indicate that

electric trucks should be included. Electric trucks are more energy efficient than electric vans (EPRI/EVAA, EVA/DC).

Several reviewers (EPRI/EVAA, EVA/DC, INEL) believe that the EV weights are too high, which in turn affects energy efficiency. In particular, EPRI/EVAA disagrees with the assumption that there will not be preferential shifts in the use of lighter materials in the EV shell. EPRI/EVAA believes that CVs will eventually use these lighter materials but CV use will lag behind EV use of such materials.

Alternatively, several other reviewers (API, Mobil Oil, Sierra Research) believe that the EV energy efficiencies used in this report are overly optimistic. Sierra Research asserts that EV energy efficiency estimates ignore a loss of charge during periods of inactivity. These reviewers (API, Mobil Oil, Sierra Research) are also concerned that the EVs characterized may not be really comparable to the CVs they would replace and should be. For example, the EVs characterized have lower aerodynamic drag and rolling resistance than the CVs (Sierra Research).

Another concern is with the assumption regarding EV life. According to EVA/DC and INEL, it will be longer than was assumed in this analysis. (This analysis assumed the same vehicle life, 130,000 miles, as that of a CV.)

C.1.3 Other

Several reviewers disagree with the assumption that EVs will replace CVs on a 1-for-1 basis (API, EVA/DC, Mobil Oil, Sierra Research, WSPA). API and Mobil Oil believe that EVs will supplement CVs and actually extend the life of older, dirtier CVs. Because the annual EV mileage estimates are thus too high, Sierra Research asserts that the estimates of the benefits of using EVs are too high while EVA/DC believes that there is less need for additional utility capacity under any scenario.

C.2 EV Characterization: Response to Comments

The battery and vehicle characterizations were initiated in 1993 and completed in early 1995. At that time, all four battery types selected were considered likely to be used in EVs (though by the end of this time period the Na-S batteries were less likely). EV technology is rapidly evolving. We would make different battery choices now. Similarly, when the characterization was conducted, EV models were dominated by passenger cars and vans; there were no (or very few) prototype electric light-trucks. We would include electric light-trucks now.

As is evident from the comments, there is a range of opinion about whether our assumptions regarding battery life and vehicle energy efficiencies are realistic or not. Some reviewers find us too conservative and others too optimistic. Certainly any analysis we conducted now might cause us to make some changes in our estimates of these two factors. However, at the time we developed our characterizations, we had our estimates externally reviewed. Based upon that external review, we believed our estimates and assumptions to be reasonable.

More specifically, it is true that the EVs characterized have lower rolling resistance and drag coefficients than the CVs characterized. The vehicle characterizations assume the same initial curb weight for EVs and CVs (which is subsequently modified for EVs to remove the weight of the internal combustion engine and add in the battery weight), but other vehicle characteristics are different based on projections available in

the literature at the time this analysis was conducted. EVs and CVs of the same vehicle type thus have similar body weights, carry the same payload, provide the same daily travel service, and are evaluated for their energy efficiency over the same driving cycles. We characterize them as comparable, but not identical.

It is also true that we did not account for the potential effect on EV energy efficiency of a loss of charge during periods of inactivity. This analysis assumes daily recharging (for fleet vehicles, weekdays only) and no lengthy period of inactivity. On other issues such as whether there will be a preferential shift to lightweight materials in EVs, what the life expectancy of EVs is, or whether there will be a one-for-one replacement of CVs by EVs, there is no "right" answer. There is reasonable basis for the assumptions we made.

C.3 CV Characterization: Key Comments

Several reviewers disagree with the CV fuel economy assumptions and estimates. API and Mobil Oil think that the CV energy efficiency estimates are too low. The report shows little improvement in CV energy efficiency over time, while much greater improvements are indicated for EVs. The assumption regarding minimal improvement in CV energy-efficiency is made in spite of fact that fuel-efficient technologies are being introduced to CVs. Alternatively, EVA/DC thinks the CV fuel economy estimates are overly generous.

Many reviewers believe the CV operating emission estimates are out-of-date and/or too high (API, EPA, Mobil Oil, Sierra Research, WSPA). EPA says they are not up-to-date per Enhanced I&M, CA Phase II RFG, etc. API, Ford, and Mobil Oil say that they do not include NLEV or Tier II and should. API and Mobil Oil disagree with the assumption of increased emissions on the LA-92 cycle. API, Mobil Oil, and Sierra Research indicate that, according to EPA, use of MOBILE5a overestimates CV emissions. Alternatively, EVA/DC believes use of MOBILE5a underestimates CV emissions.

Bekken of CARB, EPRI/EVAA, and INEL believe the study should have characterized CV operation and maintenance needs and wastes/residuals (e.g., engine oil, water pollution). EPRI/EVAA believes that the need to replace CV vehicle components should have been included.

C.4 CV Characterization: Response to Key Comments

The baseline CV included in this analysis was characterized in 1994. The CV fuel economy used here is based on the Energy Information Administration's 1994 projections of CV fuel economy. With respect to CV operating emissions, even today, neither NLEV nor Tier II are foregone conclusions. With the CVs, we used what was certain. We did include the enhanced I&M program. We did not use California Phase II RFG for the LA runs because we wanted to use the same model (MOBILE5a) for all four regions and MOBILE5a does not allow the user to input Phase II California RFG. We used CARB 1993 data to adjust (increase) the FUDS cycle results to LA-92 cycle results. However, while we can explain why we made the assumptions we did, we recognize that we might develop different estimates if we conducted this analysis today.

We did examine the CV engine oil issue, though we did not include it in the report. We believe one might assume that engine oil is replaced approximately 25 times over the life of a CV for a total of 25 gallons. Engine oil can be recycled, burned, or illegally disposed of. Ideally it should have been included, but our assessment was that its impacts on the overall study results would have been small. The ultimate focus of the study was energy use, oil use, and criteria air pollutants, but not water pollutants and solid waste.

With respect to the replacement of CV vehicle components, only the major components that must be replaced on a regular basis in every CV and that are unique to CVs as opposed to EVs (i.e., not tires) need be considered in a comparative analysis such as the EVTECA. While some belts and the CV battery might always have to be replaced, they are not "major".

C.5 Scenarios: Key Comments

There are two key comments on the scenarios. INEL points out that the EV mandate delay causes a large error in the number of EVs in the 1998-2002 period, particularly in LA. Sales of zero-emission vehicles (i.e., EVs) now are not required until 2003, rather than beginning in 1998. EPRI/EVAA and EVA/DC state the regions selected for analysis were poor choices.

C.6 Scenarios: Response to Comments

The scenarios were developed before the mandate delay. Thus, we do not characterize the scenarios as being in "error" with respect to the number of EVs in them. They simply reflect expectations at the time they were developed.

We recognize that other studies might choose other regions to analyze. Assuming that EVs might eventually penetrate throughout the U.S., we thought it reasonable to examine the effects of such penetration in regions with a wide variety of climates (in order to evaluate the impacts of different heating and cooling requirements) and which had significant differences in their power plant fuel mixes. All four regions chosen are among the 10 worst ozone nonattainment areas in the country and could be expected to benefit in terms of reduction of ozone-precursors from significant penetration of EVs.

C.7 Electric Utility Analysis: Key Comments

C.7.1 General assumptions

EPRI/EVAA and EVA/DC state that the assumptions used in the utility modeling are not correct. Looking just at PEPCO (one of two utilities modeled in the Washington, DC area), EPRI/EVAA concludes that:

- a) the dispatch modeling used is not relevant to the electricity market which will exist before 2010;
- b) this study does not recognize that PEPCO's older coal-fired units will be replaced by natural gas units according to FERC; and
- c) the study does not consider the impact of CAAA Titles IV and I on PEPCO's NOx emissions.

Further, the scenarios that assume combustion turbines (CTs) will be added to respond to any additional capacity requirements associated with EVs are incorrect. EPRI/EVAA is not aware of any utilities planning to add CTs to meet off-peak requirements. EPRI/EVAA believes that these scenarios should be removed from the analysis (EPRI/EVAA). Finally, EVA/DC believes that the focus on utilities in specific metropolitan areas is not relevant.

C.7.2 Utility deregulation

Several reviewers pointed out that electric utility deregulation will cause major shifts in electric generation, independent of EVs, and that the EVTECA dispatch results will be impacted by deregulation (EPA, EVA/DC, INEL). The units used to charge EVs will not necessarily be local power company facilities (WSPA).

C.7.3 Economic dispatch

Ford believes that the assumption of pure economic dispatch is wrong. Instead utilities consider cost, generation response time, and generating efficiency.

C.7.4 Time/type of EV recharging

The report presents results for unconstrained charging and off-peak charging as though they are equally likely. EPRI/EVAA and EVA/DC believe that time-of-use rates make the unconstrained charging scenario unrealistic. INEL believes that EV charging will be largely off-peak and that the report should conclude so: unconstrained charging of EVs seems unrealistic for more than 10% of them. However, INEL also points out that the report omits opportunity charging, which, INEL states, thereby ignores a large potential effect. The timing of opportunity charging is different than in the unconstrained option: opportunity charging occurs just after arrival at work or at a shopping mall/district, while unconstrained charging is assumed to begin when the trip home from work ends. Ford also believes fast charging should be evaluated.

C.7.5 Fleet vehicle recharging

EPRI/EVAA states that fleet vehicles will be used and charged on the weekends as well as weekdays, unlike the report assumption that they are only used on weekdays. Ford states that the time of fleet vehicle charging may be affected by number of charging stations available. The report assumes one charging station for each fleet vehicle.

C.7.6 Methodology

Several reviewers (EVA/DC, Sierra Research, WSPA) disagree with the use of incremental system emissions (ISE) estimates in the calculation of EV total energy cycle emissions estimates (see definitions in the next paragraph). Sierra Research and WSPA believe that use of ISE is wrong and should be replaced by marginal system emissions (MSE) results. Use of ISE understates EV emissions (Sierra Research). EVA/DC states that both ISE and MSE estimates are the least accurate estimates for the long term (i.e., average system emissions (ASE) estimates are more accurate).

ISE estimates are defined in the report as the difference in emissions estimates between a base case simulation with no EVs (and thus no EV charging demand) (call this simulation Sim #1) and a simulation which accounts for EV demand (Sim #2). This latter simulation varies by EV market penetration scenario and EV charging regimen. MSE estimates are defined as the difference between a base case simulation assuming no EV demand, but with capacity additions required to maintain system reliability for a specific EV demand (Sim #3), and the simulation which accounts for that EV demand (Sim #2). ASE estimates present the "average" emissions estimates for the simulation which accounts for EV demand (Sim #2). Appendix C provides a more detailed description of these three methods of estimating emissions.

Sierra Research states that additional power demand for EVs is only a small portion of expected increases in future total electricity consumption. New power plants will be required for all uses. It believes that allocation of any specific emissions benefit with EVs to specific additional capacity is misleading.

C.7.7 Other

The literature referred to in the utility dispatch section is dated (Sandia). The terminology is unclear (Bekken of CARB). Use of renewables in power plants have not been adequately considered (EVA/DC). Electromagnetic field emissions should at least be mentioned (Sandia). An explanation of why the off-peak results were only run for the summer should be included (Bekken of CARB).

C.8 Electric Utility Analysis: Response to Comments

The utility analysis was largely conducted from 1993 through early 1995. A draft utility report was sent out for review in July 1995. It received no substantive comments: i.e., no comments from the regional utilities indicating concerns with the analysis.

The time period during which this analysis was conducted preceded the current initiatives regarding utility deregulation that are sweeping the country. We recognize that deregulation will affect which power plants would be used to provide the electricity for EVs. The results of the utility analysis would be different now if we accounted for deregulation. However, deregulation is still underway (i.e., not yet final) and without further analysis we can not project what the effects would be.

With respect to EPRI/EVAA's comment that the utility analysis does not recognize that PEPCO's older coal-fired units will be replaced by natural gas units, we may indeed have a different retirement schedule than PEPCO currently has. We do not know. In general, we used data provided by the utilities themselves and their regulators. In PEPCO's case, we used information provided by a consulting firm. However, use of a different retirement schedule should not affect the essential results of the study for PEPCO. The essential results are those that estimate the *incremental* impact of EVs on PEPCO. The essential results should remain intact because the study estimates that very little coal will be used to meet the incremental generating requirements of EVs in the PEPCO region. Appendix Table C.6.1 shows coal to provide well below 1% of the incremental generating requirements of EVs in the unconstrained charging cases for PEPCO.

Similarly, we believe that the effects of the CAAA requirements were included in the data provided by the utilities. However, actions taken subsequent to the conduct of this analysis which are designed to help regions attain NAAQS (i.e., OTAG's recommendation to increase NOx controls) would change the emissions estimates developed here. Still, Appendix Table C.6.1 also shows that 93% of incremental charging requirement of EVs is met with low-NOx natural gas.

One comment requested that we remove from the analysis the runs in which combustion turbine (CT) units are added to provide additional capacity. We included CTs because (a) in the past utilities that need peaking capacity installed CTs and (b) to provide a range of possibilities instead of just assuming the addition of combined cycle (CC) units.

We agree that the scenarios which assume 100% unconstrained charging of EVs are unlikely. Using these scenarios was a good starting point, however, because (a) such scenarios provided analytical flexibility by providing a baseline case to which a variety of policies affecting EV charging times could be applied and

(b) they represent the existing situation for many utilities. Use of these scenarios also has generated some interesting results. Specifically, with unconstrained charging, substantial EV demand in the Houston case resulted in a "cleaner" total electricity system when CC capacity was added than existed without EV demand. In effect, "dirty" power plants were knocked far down in the dispatch order. Still, off-peak charging is far more likely than unconstrained charging, particularly if there is substantial EV use.

We did not include opportunity charging and fast charging of EVs in our analysis because a) we believe that, in the long run and with significant EV demand (as in our High scenarios), utilities will not encourage either and b) the total electricity demand from either of these charging regimens would be small relative to total EV demand and therefore the impact on the EVTECA results would be small. Alternatively, we agree that some charging of fleet vehicles on weekends will occur. Absence of weekend charging is an oversight in our analysis.

With respect to the use of ISE, MSE or ASE estimates, we still believe that the methodology generating ISE estimates is the correct approach for the total fuel cycle analysis. We are interested in results which represent a "world with EVs" versus a "world without EVs". The ISE estimation methodology most closely approximates the difference between those worlds.

We did consider renewable resource additions in our analysis. It was concluded that the option of adding renewable technology capacity was not a strong possibility in the time frame of this study. Funding and time constraints prohibited additional runs that would have looked at the effects of renewables.

We only simulated utility dispatch to meet off-peak charging demand in the summer (as opposed to year-round) because of funding constraints. The summer season was chosen because we are particularly interested in the changes that EVs will bring in ozone-precursor emissions.

C.9 Materials Analysis: Key Comments

C.9.1 Battery recycling

Several reviewers state that the effects of battery recycling need to be more fully considered than they have been. Sandia believes that there are various citable studies on battery recycling that could be more fully utilized (Sandia). Bekken of CARB asked whether it is realistic to largely assume that battery materials are not recycled. At least second generation batteries should be able to use recycled materials. API and Mobil Oil indicate that battery recycling could occur in-basin (the report assumes recycling is all out-of-basin) and that this should be addressed. EPRI/EVAA and EVA/DC state that nickel will be recycled and this recycling will significantly reduce the estimated SO₂ emissions associated with battery manufacturing. EVA/DC believes that an increase of 8 to 11 times in SO_x emissions with EVs, due in large part to SO₂ emissions from nickel production, simply would not be permitted, so we should assume increasing regulation of the nickel production process.

C.9.2 Lead emissions

The projected lead emissions associated with EV use seem very high according to EVA/DC and Sandia. Sandia asked that we check the inputs and results and then clarify the cause of the high emissions levels. Both lead and copper production produce lead emissions and we should state which is most significant

(Bekken of CARB also made this point). Bekken of CARB could not duplicate or approximate the lead results with the existing information in the report. Bekken of CARB also wanted to know why the emissions from secondary production of lead are higher than those from primary production.

C.9.3 Other

EPRI/EVAA state that the report should assume greater levels of recycling of all vehicle materials than it has. EPRI/EVAA also assert that if the Na-S and Ni-Cd batteries are removed from the analysis (because they are no longer likely to be used in EVs), the emissions associated with battery manufacturing (especially SOx and particulates) will be significantly reduced. Ford states that the manufacturing emissions do not match those of a MIT/Ford report. API and Mobil Oil fault the report for not reporting increases in heavy metals with EVs.

C.10 Materials Analysis: Response to Comments

We agree that battery materials are likely to be recycled. Lack of data on battery recycling processes prevented us from developing credible estimates of the emissions associated with recycling the Ni-MH, Ni-Cd, and Na-S batteries. We had already reviewed many of the studies to which Sandia referred us; they lacked the specific, quantitative emissions data required for this analysis. For future analyses which examine the impact of nickel-based batteries, one might assume that 95% of the nickel used in batteries will eventually be recycled and that in the recycling of nickel only fuel combustion emissions would be generated (i.e., not emissions from nickel smelting). Funding constraints prevented us from conducting such an analysis, which we believe would be desirable. We also agree that some battery recycling will occur within metropolitan regions.

The lead (Pb) emission results should be used cautiously for a number of reasons. We ourselves are puzzled by the fact that the U.S. Environmental Protection Agency's Compilation of Emission Factors (AP-42) reports higher lead emissions per pound of recycled lead than can be derived from its emission factors for primary lead production. Users of Table D.4.24 (primary lead smelting) should disregard the footnote on lead emissions: the emission factor of 0.19 lbs lead emissions/ton of primary lead that is used in the EVTECA is the correct emission factor. It was derived from the AP-42 emission factors for various stages of primary lead production and assumes 18.2 tons of lead sulfide ore per ton lead produced.

However, Tables 8-8 and 8-15 report the lead emissions rate for lead and lead-acid batteries incorrectly. The value in Table 8.8 should read 265 lbs lead emissions/ton of lead and the value in Table 8.15 should read 0.0915 lbs lead emissions/1000 lbs Pb-acid batteries. All of these errors would have been corrected during an edit of this report, but there would be no change in the final total lead emission results. All the total energy cycle lead emission results presented in the Synopsis and Section 2 of Volume I and Appendix E of Volume III are correct.

The traceability of the Pb-emission results is difficult. Lead emissions occur in lead, copper, steel, iron, aluminum, plastics, rubber, ceramics and nickel production. One can get a rough estimate of the lead emissions associated with EV and CV production by:

- a) only considering lead and copper production;
- b) determining the lead and copper weight of a CV and the EV shell of a Pb-acid EV of the same size as the CV (from Tables 8.1 - 8.6);

- c) determining the lead content of the Pb-acid battery in that EV by applying the percentage that lead comprises of total Pb-acid battery content (shown in Table 8-14) to the lifetime battery weight of that vehicle (from Tables 8.4 - 8.6); and
- d) applying the material emission rates shown in Table 8.8 (corrected as described above).

This will provide an estimate for production of CVs and Pb-acid EVs, but Pb-acid EVs only make up a percentage of the total EV stock (e.g., in 2010, 14% per Table 4.2). Lead emissions are much lower with other EVs since (in this rough estimate) only the copper in the shell of these EVs generates lead emissions. So, for the average EV, one has to weight the shares of the various EV battery types.

Using this limited approach, we estimate that the lead emissions of EVs are approximately 370% higher than those of CVs in 2010. That is slightly less than the 400% to 500% increases calculated for the full fuel cycle, but again remember that the other seven materials have not been included in this quick calculation.

Examination of one total energy cycle run in which EV lead emissions are 486% higher than CV emissions indicates that the lead emissions from all battery materials (lead, plastics, nickel, etc.) comprise 85% of the total lead emissions from EVs. Nearly 90% of the lead emissions from all battery materials are from the production of lead for the Pb-acid batteries. Clearly, the lead emissions increases with EVs estimated in this report come predominantly from the production of Pb-acid batteries.

Other assessments could justifiably assume greater recycling of other vehicle materials. Eliminating the Ni-Cd and Na-S batteries would clearly change the emissions results, but if Ni-MH batteries replace them, not by much. A quick review of the Ford/MIT report indicates that it focuses on fuel combustion emissions associated with manufacturing vehicle materials in China and omits process emissions (i.e., nickel smelting). The EVTECA analysis includes both types of emissions. Ideally we would have reported heavy metals production, but additional data gathering would have been required.

C.11 Total Energy Cycle Results: Key Comments

According to several reviewers, the report's presentation of results is biased in favor of either EVs or CVs. API and Mobil Oil say that the reporting of the emission reduction benefits of EVs is biased in favor of EVs. Reductions are reported as percents, but increases are reported in whole numbers. According to EPRI/EVAA, where we report just total emission results, as opposed to both total and in-basin results, the presentation is biased in favor of CVs. They contend that total emissions should never be presented without in-basin emissions results.

Bekken of CARB, EPA and Ford would like to see the total energy cycle results for Los Angeles and Chicago completed. EPA believes that since the the two off-peak total energy cycle results are nearly the same in each region, their reporting should be combined.

C.12 Total Energy Cycle Results: Response to Comments

Our intent was to present the results in an even-handed manner. We too wish that funding had permitted the completion of the total energy cycle runs for Chicago and Los Angeles. It was always our intention to conduct those runs. In the editing process, we could have combined better the off-peak results.

C.13 Other Specific: Key Comments

Several other key comments which can not easily be categorized were made by the reviewers. EPA believes that N₂O emissions should be included, so that greenhouse gas emissions could be estimated. Ford states that household mileage should be updated. EVA/DC would like more flow charts presenting the combination of the various subprocesses included in the the energy cycles. API and Mobil Oil fault the study for omitting economics. Mobil's quick analysis of the report's results indicate that EVs are not cost-effective for VOC reductions in DC.

C.14 Other Specific: Response to Comments

These are all reasonable comments. On the subject of economics, the study was not designed to include economics. Other studies exist or are underway which can be used to estimate the costs of manufacturing and using these vehicles.

C.15 General: Key Comments

There is a substantial range of opinion regarding this report. Much of the opinion is negative, but not all. Selected comments include the following:

- 1) EPRI/EVAA states that the results are not credible. The document is dated. The level of detail of the analysis is inconsistent. Significant upgrades of the data, analysis and presentation will be necessary to make the report credible;
- 2) EVA/DC states that the EVTECA study is fundamentally flawed and outdated. The study should be recalled, updated and restructured into a dynamic model;
- 3) Ford believes that many assumptions are questionable and additional analysis is required to address these issues before the report is completed;
- 4) WSPA endorses the conclusion of Sierra Research that the results are driven by assumptions that consistently overstate the emissions associated with CVs while understating the emissions and energy consumption associated with EV recharging;
- 5) API and Mobil both emphasize that the study is overly generous to EVs;
- 6) INEL believes the report contains some excellent analysis, but believes the improvements it suggests should be made, otherwise the report will appear out-of-date and be easy to criticize;
- 7) Sandia is concerned that the report is already dated and not yet published;
- 8) EPA believes the report is very well done. However, the report raises policy implications that could or should be addressed in the report itself. For example, the study should call attention to the fact that there are substantial tradeoffs in the emissions results with EVs;
and
- 9) Bekken of CARB wants to know if the models and data used in the EVTECA are available for others to use.

C.16 General: Response to Comments

Because of rapid changes in the development of EVs and utility deregulation, this report is dated. It reflects EV and utility characterizations made in the 1993 to 1995 time period. However, we believe it contains useful information upon which to build future evaluations of EVs. CARB apparently also recognizes the

EVTECA is a good starting point because its RFP for a life cycle analysis (LCA) of EVs asks the analysts to make use of this report, among others, where possible.

Thus, rather than updating and revising the report, the report is being made available to interested parties, along with the criticisms of it. It is hoped that the availability of this report will allow future studies, such as CARB's EV LCA, to address the shortcomings of this study and to do so efficiently, without having to reproduce much of the information in the study. DOE also plans to build on the information gathered in this assessment to develop a more flexible tool to model the energy cycle emissions of EVs, one which will be easier to keep up-to-date and easier to use in conducting sensitivity analysis. The model will be designed to allow users to input some of their own assumptions regarding EV use: e.g., battery type mix, number of battery replacements, vehicle energy efficiency, daily EV use, and power plant fuel mix.

Synopsis

This synopsis summarizes the methodology (S.1), results (S.2), and conclusions (S.3) of the electric vehicle total energy cycle assessment (EVTECA).

S.1 Electric Vehicle and Conventional Vehicle Energy Use and Emissions Inventory

The EVTECA report presents the results of a total energy cycle assessment (TECA) of electric vehicles (EVs). It contains an inventory of the energy use and emissions associated with using EVs in a number of metropolitan areas of the United States. The inventory includes energy use and emissions from electricity generation to charge EV batteries, the fuel extraction and transport needed to support this electricity generation, and battery and vehicle manufacture. These energy use and emissions estimates are compared to a similar inventory of conventional vehicles (CVs) operating on reformulated gasoline (RFG). The CV inventory includes vehicle operation; the extraction, transport and processing required to supply vehicles with RFG; and vehicle manufacture. Comparison of the EV and CV inventories under various scenarios allows us to estimate the changes in vehicle-related energy and emissions that would occur with the introduction of EVs.

EVs using four battery types are characterized. The four battery types are: Advanced Lead-acid (Pb-Acid), Nickel-Cadmium (Ni-Cd), Nickel-Metal Hydride (Ni-MH), and Sodium-Sulfur (Na-S). These four battery types were selected in 1994 based on what vehicle and battery manufacturers were then working on. (Different batteries might be selected now.) Cars and vans using these batteries are characterized in terms of the following factors:

- Weight
- Battery and vehicle shell (rest-of-vehicle) materials
- Energy efficiency
- Use in fleet vs. household market niches
- Daily travel, and
- Daily recharge requirements.

Many of these characterizations vary by time period of EV manufacture and use. Therefore EVs were characterized for three time periods: 1998-2002, 2003-2007, and 2008-2010.

Of the factors, energy efficiency of the EVs is one of the most significant. Estimates of EV energy efficiency are wide-ranging. EVs produced in the latter years of this analysis are estimated to achieve the following base energy efficiencies in urban driving:

- Cars: 0.21 kWh/mile to 0.25 kWh/mile;
- Minivans: 0.23 kWh/mile to 0.26 kWh/mile; and
- Full-size vans: 0.38 kWh/mile to 0.43 kWh/mile.

The ranges generally reflect differences between battery types. The base energy efficiencies in turn are affected by seasonal air conditioning and heating requirements, which vary by metropolitan area. The effect of these requirements are accounted for in the TECA.

These estimates of vehicle energy efficiency combined with total daily travel and recharge requirements and total market penetration determine the total daily electricity demand generated by EVs in a region. High and low EV market penetration scenarios are presented for four metropolitan areas: Los Angeles,

Houston, Washington, D.C. (hereafter referred to as Washington) and Chicago. 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 VOC emissions); (b) they are diverse with respect to the current mix of fuels used to generate electricity for their respective regions; and (c) their climates are different.

For each metropolitan area, the study examines one market-penetration scenario that assumes implementation of a California ZEV-like mandate (which requires 10% of LDVs sold to be EVs, beginning in 2003). This is the low market-penetration scenario for Los Angeles and the high market-penetration scenario for the other three metropolitan areas. In the scenarios based on this California ZEV-like mandate, the study estimates that 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. The EVs are projected to replace CVs and their daily travel on a one-for-one, equivalent-use basis. The electricity demand generated by these vehicles represents approximately 0.4% to 1.1% of the estimated electricity demand without EVs in these four regions in 2010 (as estimated in this study).

Estimates of emissions generated by utility power plants in response to such market penetration levels are presented. The utility analysis includes development of (a) a baseline forecast of generating requirements for each of the four regions and (b) the additional capacity requirements brought on by the various EV market penetration scenarios and EV charging assumptions. EVs are assumed to be recharged either as soon as they return "home" (unconstrained charging) or under some type of controlled charging regimen which results in off-peak charging. To maintain system reliability, additional power plant capacity is required when EV market penetration is high and unconstrained charging is assumed. Additional capacity requirements are much lower with off-peak charging. For example, unconstrained charging in Houston necessitates the addition of 171 MW by 2010. The same demand served by off-peak charging results in a 0.1 MW additional capacity requirement. The 171 MW represent approximately 1% of existing capacity.

Average, incremental and marginal energy use and emissions estimates were developed in the utility analysis for each region for both low and high EV market penetration scenarios, for both unconstrained and off-peak charging (three separate cases), and assuming that either combined cycle or combustion turbine units were added to fill the additional capacity requirements. We could not examine all of these variations in the total energy cycle simulations. Instead, we chose to focus on the incremental energy use and emissions results assuming (a) unconstrained charging and (b) the off-peak charging case which required the least additional capacity to maintain system reliability (i.e., the one that made greatest use of existing or currently planned power plants). Incremental energy use and emissions are defined as the difference between a base case simulation assuming no EV charging and one which accounts for EV charging.¹

In addition to estimating energy use and emissions in utilities alone, the EVTECA includes the energy and emissions associated with producing and delivering the fuels used in power plants to generate electricity for EVs. Similarly, a characterization of the energy and emissions associated with producing EV battery and vehicle shell materials is presented. These two characterizations combined with the energy use and emissions from utilities produce the inventory of the energy use and emissions associated with EV use. This total inventory was generated only for two of the four metropolitan areas (Houston and Washington) and only for the high EV market penetration scenarios in each. Time and funding constraints limited the number of regions and scenarios for which the total energy cycle simulations could be completed.

¹ "Marginal" estimates are defined here as the difference between a base case simulation assuming no EV charging, but with the capacity additions required with EVs, and a simulation which accounts for EV charging. "Average" estimates aggregate the EV-related emissions with non-EV-related emissions and present an "average" for all electricity demand.

A comparable inventory of energy use and emissions associated with the CV energy cycle was also developed. CV weight, materials composition, and fuel economy are characterized. In the latter years of the analysis, CVs are estimated to achieve the following fuel economy (base case) in urban driving: 29 mpg for cars, 23 mpg for minivans, and 15 mpg for full-size vans. As with the EVs, seasonal adjustments are made to account for air conditioning and heating requirements.

The CV vehicle operating emissions are estimated using EPA's MOBILE5a model. The CVs are assumed to use RFG oxygenated with MTBE in Los Angeles, Washington, and Houston and ethanol in Chicago. Emissions associated with producing RFG (and the crude oil, natural gas, oxygenates, and other materials that feed into its production) were estimated for Houston and Washington. The energy use and emissions associated with vehicle materials production for CVs was estimated using the same materials characterization as for EVs, though the materials content of the CVs differs somewhat from that of EVs. Together, the energy use and emissions associated with CV operation, RFG production and transport, and vehicle manufacture comprise the CV total energy cycle inventory.

The EV and CV inventories cover energy use by fuel type, and air and water pollutants and solid waste. The water pollutants and solid waste characterization is not thorough. For example, we collected no data on water pollutants and solid waste from power plant operations. In the report, we present process-level water pollutant and solid waste data where we collected them, but we do not analyze water residuals or solid waste across the full energy cycles because we collected them for few of the processes.

S.2 Results

S.2.1 Individual Stages of the Energy Cycles

The total energy cycle results are presented below (S.2.2). In this section, we highlight several of the key findings of the analysis of the individual stages of the energy cycle. Specifically, the utility analysis alone demonstrates that emissions associated with electricity generation to meet EV charging requirements vary from region to region and within regions depending upon what the dominant power plant fuel types are in a region, what type of EV charging regimen (unconstrained or off-peak) is assumed, what type of generating capacity is added to meet the EV charging demand, whether economic or emission-constrained dispatch is assumed, and what season of the year is being examined. The emissions results generated also depend on the methodology used to compute EV-related emissions: average, incremental or marginal.

Comparing the incremental emissions associated with electricity generation for EV charging to CV operating emissions in all four regions (a comparison typically made and the only comparison we can make for the Los Angeles and Chicago regions in the EVTECA report), we find that:

- VOC and CO emissions associated with EVs are always much lower (97% or more) than those from CVs;
- CO₂ emissions are also always lower, but there is substantial variation across the regions and charging regimens in terms of the level of reduction;
- For the regions for which we have estimates, CH₄ emissions are lower;
- NO_x, SO_x and TSP from EVs can be higher or lower.

Table S.1 presents annual emission comparisons for the scenario with the California ZEV-like mandate. These comparisons present total, not in-basin, emissions from power plants providing the electricity to charge EVs and CV operation. In-basin emissions are those that specifically contribute to a region's emissions inventory.

(In-basin results for the total energy cycle are discussed below). Table S.2 presents emissions in summer for the complete set of scenarios (annual emissions were not estimated for all scenarios, but emissions in summer closely track annual patterns in most cases).

With respect to the vehicle materials analysis, we need to emphasize that an EV's shell and the CV to which the EV is compared will be made up of essentially the same materials. For example, each will be approximately 85% iron, steel, aluminum, plastic and rubber. No preferential shifts in use of lighter materials for EVs is assumed. Given that the EV shell is lighter than the CV, its production generates fewer total emissions from these materials. However, the production of EV batteries and motors and controllers generate other emissions. The batteries are expected to be replaced at least once in the life of each EV. Therefore, it is not surprising that the total energy cycle results indicate that the manufacture of EVs will generally lead to more criteria air pollutant emissions than the manufacture of CVs.

S.2.2 Total Energy Cycles

Energy Results

Figure S.1 shows the total energy resource consumption, by fuel type, for the scenarios examined for their total energy cycle implications. The two CV energy cycles (for Houston and Washington) show similar levels of total energy consumption per vehicle mile traveled (approximately 6750-7000 Btu/mile). The CV energy cycles consume considerably more energy resources than any of the EV scenarios: from 15% to 40% more. The EV energy cycles use from 3900 to 5750 Btu/mile.

Of particular interest are the total oil requirements of the two energy cycles. Total oil use is greatly reduced with EVs: over 85% in Houston and 50%-60% in Washington. The reduction is lower in Washington because fuel oil is projected to provide 50% or more 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.

The differences among the per-mile energy resource consumption values for the EV scenarios is caused by a number of factors, but the most important is the variation in the mix of generating units and power plant fuels used in the scenarios. Different units require different fuel input to produce a unit of electricity. For example, in both Houston and Washington, the scenarios that assume that CT units are added in response to EV demand use more total energy than those that assume that CC units are added to meet this demand. This is to be expected, because CC technology is more energy-efficient than CT technology.

The energy results presented here are also dependent on the fuel economy of the CVs characterized in this analysis and the energy efficiency of EV operation. The average energy efficiency of CVs (cars and light trucks) that would be replaced by EVs in 2010 is estimated to be approximately 5500 Btu/mile (summer season results) or a fuel economy of 21 mpg. The average energy efficiency of EVs (not accounting for electricity generation losses) is about 1150 Btu/mile. This is equivalent to 0.34 kWh/mile or 100 mpg.

Environmental Results

Selected environmental results for one scenario are shown in Figure S.2. They are the results for Washington in 2010 assuming unconstrained charging of EVs and the addition of combined cycle units to maintain system reliability. The direction of the total energy cycle results for this one scenario reflect the overall emissions results for the remaining Washington and Houston scenarios, as described below.

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 range from 26% to 64% in unconstrained scenarios.
- **VOC:** VOC emissions are dramatically reduced by EVs. Total VOC reductions in the unconstrained scenarios are approximately 90%. In-basin VOC emission reductions range from 98% to 99%.
- **CO:** CO emissions are also dramatically reduced by EVs. Total CO is reduced from 85% to 90%. In-basin CO emissions are reduced from 97% to 99%.
- **NO_x:** All EV scenarios examined lead to NO_x reductions, both total and in-basin, both annual and summer. However, the results show that the level of reduction can vary greatly between regions and is highly dependent upon the type of EV charging assumed. For Houston, total NO_x is reduced from 7% to 96%, while for Washington, NO_x is reduced from 25% to 40%. In Houston, the in-basin NO_x reductions can be as low as 25% and as great as over 100%. In Washington, the in-basin reductions range from 84% to 97%. The NO_x-related emissions of EVs are strongly influenced by which type of power plant is added under unconstrained charging and whether unconstrained charging or off-peak charging is used.

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

- **CH₄:** EVs generally 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 annual increases range from 17% to 47%. However, there may be instances where CH₄ emissions could be roughly similar to those of CVs. In several of the Washington summer scenarios, slight reductions (less than 5%) in total CH₄ are achieved.
- **TSP:** TSP emissions will increase with EVs due to vehicle and battery manufacture and power plant operations. The annual increases range from 29% to 64%. However, in-basin TSP emissions are generally lower with EVs. In-basin reductions of up to 75% were estimated. We do not have the data to present PM-10 or PM-2.5 results.
- **SO_x:** SO_x emissions are between eight and eleven times higher in the EV scenarios. The major source of the emissions is not power production, but battery manufacturing (particularly the nickel batteries). In-basin SO_x emissions (from power plants) increase with EVs, but the increases are not as great as the total energy cycle increases. Use of unconstrained charging and the addition of combined cycle units in fact can lead to lower in-basin SO_x emissions with EVs in both the Houston and Washington areas.
- **Pb:** Lead emissions increase approximately 400% because of the use of lead-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, though some recycling of battery materials (which was not specifically addressed in this analysis) could occur in-basin.

While we report in-basin results, these results should be treated with more caution than the total results. In this analysis, we specifically estimated the in- and out-of-basin location of power plants providing the electricity to meet EV demand. We also reviewed crude refining capacity and oxygenate production capacity for each region to determine the likelihood of in-basin RFG production. We determined that in-basin refining and oxygenate production would be very likely in Houston, but not likely in Washington. All CV vehicle operation replaced by EVs is assumed to be in-basin. However, with respect to vehicle and battery manufacture, production of fuels for use in power plants and production of ancillary energy, we simply assumed that these activities occur out-of-basin. In spite of this limitation, we believe it worthwhile to present the in-basin results to give a sense of their potential direction.

S.3 Concluding Remarks

A few concluding remarks are as follows:

1. Relative to the CVs they replace, EVs reduce oil use substantially, but the level of reduction varies by region. On a total energy cycle basis, oil use by LDVs is reduced by over 85% in Houston and by 50-60% in Washington. The variation in results between the two cities is due to differences in estimated use of oil-fired power plants to generate electricity for EVs.

2. The results of this study show that simply comparing the CV vehicle operation emissions to the EV power plant emissions could lead to incorrect conclusions about the relative emissions contributed by CVs and EVs. In the CV energy cycle, the CV operation stage generates the bulk of the CO₂, NO_x, VOC and CO emissions, but vehicle manufacture is the most important contributor to TSP, SO_x, and Pb emissions. Fuel production and ancillary energy (energy used in miscellaneous processes within the various energy cycle stages) production generate the greatest share of CH₄. In the EV cycle, power plants generate the greatest share of CO₂. Vehicle manufacturing generates the greatest amount of TSP, SO_x, CO and Pb. Fuel production generates the greatest amount of CH₄ and VOC. Depending on the EV charging regimen assumed, either power plants or fuel production activities generate the most NO_x. Therefore, the results of the comparison between EV and CV total energy cycles will vary depending on which pollutant is examined, and will be different from results obtained when just the operation stage of the CV cycle and the power plant stage of the EV cycle are compared.

3. Because we did not examine the total energy cycle of EVs operating in Chicago or Los Angeles, we do not have as complete a picture of EVs as we would like. In particular, 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). How this would affect the total energy cycle results is unclear.

4. As indicated up front, the EVTECA is an inventory of EV-related energy use and emissions. It is not an impact analysis. However, to provide some perspective on the emission-reduction potential of EVs, we can examine the effect of EV-related VOC reductions on VOC inventories in Houston and Washington. (We can not go further to examine the effect of EVs on ozone levels.) VOC inventories for 1990 for these regions are available in EPA-required State Implementation Plan documents; no estimates for 2010 are available. Table S.3 presents these inventories and the in-basin VOC emissions reductions achieved with EVs in 2010 as estimated in the EVTECA. The results indicate that a California ZEV-like mandate 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.

We recognize that this is something of an apples-and-oranges comparison: e.g., the 1990 inventory does not account for the effects of RFG use in these regions which would reduce the CV VOC emission totals or alternatively the increase in total VMT that will occur by 2010 that will increase CV VOC emissions, etc. Thus the comparison in Table S.3 is not ideal. Additionally, Table S.3 only focuses on the potential effects of EVs on VOC. Similar evaluations of the regional effects of EVs on other pollutants should be made.

5. Finally, the effects of the production of various EV batteries on energy use and criteria air pollutant emissions have been included in the results presented above. However, we must place some caveats on the battery manufacture analysis. First, not all materials were characterized (though we believe the major materials have been), and those that were characterized were not always completely characterized. Second, our results assume recycling (at historical recycling rates) of the lead only, not materials in the other three battery types. Recycling of the nickel-based batteries would in particular reduce SO_x emissions from EVs. Third, 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 battery materials are extracted and batteries are produced and recycled.

CV	Conventional Vehicle	UCC	Unconstrained Combined Cycle	OCC	Off-peak Combined Cycle
EV	Electric Vehicle	UCT	Unconstrained Combustion Turbine	OCT	Off-peak Combustion Turbine

*

In this scenario, the introduction of EVs results in decreased fuel use in and emissions from all power plants serving Houston because the increased electricity demand due to EVs is projected to cause the utility company to add new, highly-efficient units and decrease use of older units that are less energy-efficient and more polluting. (See Chapter 5 for further discussion of this point.) The figure shows the decrease in fuel use as the portion below the X-axis (denoted as "0"). Increases in fuel use from other sources are offset by the decrease from older utility units, as shown by the dotted line near the top of the bar. The value shown over the bar is the net fuel use associated with EVs.

Figure S.1 Primary Energy Resource Consumption in Houston and Washington, D.C. Scenarios

Figure S.2 Comparison of Emissions in CV and EV (Unconstrained Combined Cycle) Scenarios for Washington, D.C. : Annual Results (2010)

Table S.1 Annual CV Operation Emissions Compared to EV Power Plant Emissions (tons)

Scenario	CV Operation	Power Plants for EVs (UCC)	% Reduction	Power Plants for EVs (UCT)	% Reduction
CO₂					
Houston (High)	954,760	196,913	79.4%	653,232	31.6%
Washington (High)	667,516	435,711	34.7%	469,530	29.7%
Los Angeles (Low)	2,066,900	862,596	58.3%	1,008,667	51.2%
Chicago (High, Emissions- Constrained Dispatch)	1,185,300	840,044	29.1%	1,027,198	13.3%
CH₄					
Houston (High)	148	56	62.2%	36	75.7%
Washington (High)	89	19	78.7%	17	80.9%
Los Angeles (Low)	169	NA		NA	
Chicago (High, Emissions- Constrained Dispatch)	170	NA		NA	
TSP					
Houston (High)	51	62	-21.6%	46	9.8%
Washington (High)	34	80	-135.3%	96	-182.4%
Los Angeles (Low)	111	103	7.2%	64	42.3%
Chicago (High, Emissions- Constrained Dispatch)	65	556	-755.4%	333	-412.3%
SO_x					
Houston (High)	110	-545	595.5%	752	-583.6%
Washington (High)	77	842	-993.5%	1177	-1428.6%
Los Angeles (Low)	55	10	81.8%	10	81.8%
Chicago (High, Emissions- Constrained Dispatch)	138	292	-111.6%	-459	432.6%
NO_x					
Houston (High)	1833	-872	147.6%	520	71.6%
Washington (High)	1235	590	52.2%	722	41.5%
Los Angeles (Low)	1703	-11	100.6%	901	47.1%
Chicago (High, Emissions- Constrained Dispatch)	2358	-3997	269.5%	2161	8.4%
VOC					
Houston (High)	2023	34	98.3%	32	98.4%
Washington (High)	1212	15	98.8%	17	98.6%
Los Angeles (Low)	2312	63	97.3%	35	98.5%
Chicago (High, Emissions- Constrained Dispatch)	2328	1	100.0%	39	98.3%
CO					
Houston (High)	16242	-345	102.1%	166	99.0%
Washington (High)	12776	65	99.5%	83	99.4%
Los Angeles (Low)	26270	127	99.5%	338	98.7%
Chicago (High, Emissions- Constrained Dispatch)	28090	-540	101.9%	411	98.5%

Table S.2 CV Operation Emissions Compared to EV Power Plant Emissions in Summer (tons)

Scenario	CV Operation	Power Plants for EVs (UCC)	% Reduction	Power Plants for EVs (UCT)	% Reduction	Power Plants for EVs (OFF-P)	% Reduction	Power Plants for EVs (OFF-P)	% Reduction
CO₂									
Houston (High)	300,233	70,999	76.4%	185,162	38.3%	215,650	28.2%	214,432	28.6%
Washington (High)	209,510	106,824	49.0%	121,621	41.9%	114,866	45.2%	123,763	40.9%
Los Angeles (Low)	637,000	240,287	62.3%	304,413	52.2%	275,068	56.8%	284,759	55.3%
Chicago (High, Emissions- Constrained Dispatch)	366,000	211,368	42.2%	297,194	18.8%	351,230	4.0%	324,557	11.3%
CH₄									
Houston (High)	34	17	50.0%	12	64.7%	7	79.4%	8	76.5%
Washington (High)	22	6	72.7%	5	77.3%	5	77.3%	5	77.3%
Los Angeles (Low)	47	NA		NA		NA		NA	
Chicago (High, Emissions- Constrained Dispatch)	45	NA		NA		NA		NA	
TSP									
Houston (High)	14	16	-14.3%	15	-7.1%	4	71.4%	4	71.4%
Washington (High)	9	30	-233.3%	35	-288.9%	33	-266.7%	37	-311.1%
Los Angeles (Low)	30	25	16.7%	16	46.7%	22	26.7%	22	26.7%
Chicago (High, Emissions- Constrained Dispatch)	18	119	-561.1%	108	-500.0%	164	-811.1%	139	-672.2%
SO₂									
Houston (High)	34	-131	485.3%	175	-414.7%	527	-1450.0%	552	-1523.5%
Washington (High)	24	441	-1737.5%	534	-2125.0%	493	-1954.2%	564	-2250.0%
Los Angeles (Low)	17	3	82.4%	3	82.4%	3	82.4%	3	82.4%
Chicago (High, Emissions- Constrained Dispatch)	42	-907	2259.5%	-28	166.7%	1625	-3769.0%	-190	552.4%
NO_x									
Houston (High)	448	-144	132.1%	120	73.2%	411	8.3%	415	7.4%
Washington (High)	307	154	49.8%	204	33.6%	183	40.4%	218	29.0%
Los Angeles (Low)	446	38	91.5%	318	28.7%	184	58.7%	208	53.4%
Chicago (High, Emissions- Constrained Dispatch)	568	-1181	307.9%	753	-32.6%	1021	-79.8%	703	-23.8%
VOC									
Houston (High)	471	9	98.1%	10	97.9%	5	98.9%	5	98.9%
Washington (High)	295	5	98.3%	6	98.0%	5	98.3%	6	98.0%
Los Angeles (Low)	648	16	97.5%	9	98.6%	12	98.1%	12	98.1%
Chicago (High, Emissions- Constrained Dispatch)	612	2	99.7%	11	98.2%	8	98.7%	9	98.5%
CO									
Houston (High)	3476	-63	101.8%	31	99.1%	110	96.8%	93	97.3%
Washington (High)	2309	19	99.2%	29	98.7%	23	99.0%	29	98.7%
Los Angeles (Low)	5835	39	99.3%	110	98.1%	53	99.1%	58	99.0%
Chicago (High, Emissions- Constrained Dispatch)	4682	-103	102.2%	113	97.6%	52	98.9%	74	98.4%

Table S.3 EV In-Basin VOC Reductions in 2010 Compared to In-Basin VOC Inventories in 1990: Houston and Washington (Tons/Day)

Region/Man-Made VOC Source Type	1990 VOC Inventory	2010 EV VOC Reduction	EV VOC Reduction as a % of Inventory
Houston			
On-Road Mobile	163.4	5.45	3.3%
All Other	813.4	0.47	0.1%
Total	976.8	5.92	0.6%
Washington			
On-Road Mobile	252.5	3.3	1.3%
All Other	286.1	0	0.0%
Total	538.6	3.3	0.6%

Total Energy Cycle Assessment of Electric and Conventional Vehicles: An Energy and Environmental Analysis

1.0 Introduction

Because they generate no air pollutant emissions during use, people generally view electric vehicles (EVs) as an environmentally-benign technology. Increased use of EVs is viewed by many as one solution to the air pollution problems in urban areas plagued with "smog," the condition resulting from photochemical reactions involving air pollutants such as nitrogen oxides (NO_x) and volatile organic compounds (VOC) emitted from conventional vehicles (CVs) as well as other sources. In fact, for decades CVs have been the target 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 additional processes required to support EV use -- 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 create environmental degradation at the sites of those activities. Thus, to completely understand and analyze the energy and environmental tradeoffs between EVs and CVs, we must carefully catalog the material and energy consumption and the environmental residuals for the "total energy cycle" of EVs and compare it to those associated with the total energy cycle for CVs.

This study seeks to shed light on this issue by reporting results of the first step of a Total Energy Cycle Assessment (TECA), which consists of developing a comprehensive energy and environmental inventory for EVs and CVs.¹ A TECA inventory quantifies the environmental residuals and material/energy consumption over all stages of the energy cycle. The stages include fuel extraction and transport, processing and conversion of fuels to energy, energy distribution and end-use (see Figure 1.1).

The operational phase of the EV energy cycle examined in this study includes fuel production and transport processes (for coal, oil, gas, and uranium), electricity generation, electricity transmission and distribution, battery charging, and vehicle end-use (Figure 1.2). Also included are EV shell and battery manufacture, which are considered part of the pre-operation phase of the EV energy cycle. 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 or the emissions associated with EV manufacture. The energy cycle examined for CVs includes vehicle manufacture, 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 study covers a significantly expanded scope of processes. For the purposes of this report, EVs were compared to CVs using reformulated gasoline (RFG), which we consider the "benchmark" technology in this study.

¹ Inventory analysis is the first part of a TECA. A complete TECA might also include subsequent steps, such as translating the energy/environmental inventory into ambient concentrations, assessing damages and effects on human health (i.e., an impact assessment), and examining ways to alter the system to provide the same level of service at a reduced level of energy/environmental impact (improvement assessment). These subsequent steps are not included in this analysis. TECA inventories can also cover pre- and post-operation phases of an energy cycle (e.g., construction and decommissioning of power plants or refineries), but with the exception of the EV shell and battery manufacture, these were not included in this TECA.

Figure 1.1 Energy Cycle Stages

The study looks at the potential energy and environmental effects of EVs through the year 2010 by comparing a future with substantial market penetrations of EVs to one without EVs. These effects are dependent on many factors, all of which are uncertain. The important factors include:

- level of EV penetration
- the type of technologies employed in EVs (e.g., which battery types predominate) and the amount of technological progress (i.e., improved energy efficiency) between now and the future
- the types of travel for which EVs are used
- the electric utility technologies used to provide the electricity for recharging EV batteries
- the level of CV fuel-efficiency improvement between now and the future.

To deal with some of these factors, we made assumptions based on what the study team viewed as likely future conditions. For example, based on a review of EV battery developments, we chose a specific mix of battery types to be analyzed for each of the two years included in the analysis -- 2000 and 2010.

Note: Dotted lines indicate processes in the pre-operational phase.

Figure 1.2 Stages in the EV and RFG CV Energy Cycles

For other factors, we chose to examine a range of assumptions through the use of alternative scenarios of the future. For example, to assess the impact of EV penetration rates on the utility system, we included both a case with high-EV penetration and one with more moderate EV penetration. We also included cases that assumed EV charging would occur in off-peak hours and others that assumed charging would be initiated as soon as the EVs returned "home." And, to study the potential effects of varying utility technology of choice for new capacity, the EVTECA examined cases that assumed natural gas-fired combined cycle units would be chosen to provide extra needed capacity, as well as cases that assumed combustion turbines would be chosen. (The scenarios and assumptions for the study are discussed in more detail in the next two sections of this report.)

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 fuel mixes. They are in diverse climates (which affects the efficiency of the EV batteries as well as the emissions of CVs). In addition, the distance between each of the cities and its fuel supply (e.g., distance from refinery capacity to service stations) differs, affecting energy and emissions for the fuel transport stages of the energy cycles. 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 interpretation of the effects of EVs on seasonal air quality issues.

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 marginal demand for electricity to charge the EVs could be met, and what the environmental impact of this added electricity demand would be.

The energy and environmental analysis of the operation of the two types of vehicles -- EVs and CVs -- was also handled in this study in a great deal of detail. Driving patterns and climatic factors in each urban area were studied and vehicle operating conditions (e.g., average trip lengths and region-specific heating and air conditioning requirements) were chosen to reflect the differences. Complex models were used to estimate the energy efficiency, recharging requirements, and daily recharging requirements of the EVs, and to compute energy efficiency and emissions from CVs.

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

This TECA attempted to quantify the energy and material inputs and outputs of the major processes involved in the EV and CV energy cycles. The result is an inventory of energy and emissions associated with EVs and CVs. 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 that was 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, based on SCAQMD's own analysis of EV-related emissions, are thought 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. (See Appendix A.1 for a discussion of the interactions of the study team with SCAQMD.)

The primary environmental residuals considered in the inventory analysis are the airborne emissions: carbon dioxide (CO₂), methane (CH₄), sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), total suspended particulates (TSP), non-methane volatile organic compounds (NMVOC) and lead (Pb). When data were available, liquid-borne and solid residuals were also included. A more detailed list of the pollutants that were included in the design of the study can be found in Appendix A.2. The number of processes and inputs/outputs associated with the energy cycles studied in this analysis 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 cycles. However, an effective (and manageable) TECA must trade off the benefits of increased completeness derived

from a more comprehensive assessment versus the additional resources required to achieve that completeness (PNNL 1993). This study focuses on the major processes and the input/outputs of those processes.

A formal peer review process was implemented to ensure that the EVTECA is based on the best available data and information as well as on sound analysis. The formal external peer review process included three levels: national, regional, and functional. National peer review addressed overall project issues; regional peer review focused on regional data and analyses; and functional reviews addressed specific technical areas, such as the characterization of vehicles, batteries, and RFG. Peer review of some items, such as EV penetration, occurred at more than one level to obtain alternative perspectives.

This study was conducted jointly by Argonne National Laboratory (ANL), Pacific Northwest National Laboratory (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 by the DOE Office of Nuclear Energy. PNNL provided an overall framework for the assessment, including specifying data requirements, as well as both modifying and applying a computerized (TECA) accounting tool -- the Total Emissions Model for Integrated Systems (TEMIS). NREL defined the specific scenarios to be analyzed, developed a peer-review plan (which was implemented during the course of the assessment), conducted utility dispatch modeling, conducted an analysis of (and developed environmental data for) the electric utility fuel cycles involved in charging EV batteries, and coordinated the analysis of the Los Angeles metropolitan area with the SCAQMD. ANL was responsible for battery and EV characterization, characterization of the trips to be displaced by EVs, estimation of total EVs on-road, projection of EV electricity consumption, estimation of energy and emissions resulting from battery and vehicle manufacture, and development of data for the benchmark RFG-fueled CV. ANL also managed the overall effort.

The TECA was not designed to address specific policy mechanisms, e.g., whether tax incentives, R&D subsidies, or fleet quota requirements would be good approaches for implementing an increase in EV market penetration. The technical information derived from the TEC comparisons can be used to assess the overall positive and negative affects of increased EV use in several regions (metropolitan areas) of the U.S. Further analysis would be needed to assess the merits of particular policies directed at encouraging EVs or modifying their environmental impacts.

The remainder of this report is organized in the following manner:

Chapter 2 provides a general overview of the key results of the study. Chapter 3 discusses the conceptual framework for the study and provides an overview of what processes were included in the study and how they were configured to devise the energy cycles studied under various scenarios. Individual processes and the associated assumptions are described in detail in the remainder of the report. Chapter 4 describes the vehicle analysis. The utility analysis is described in Chapter 5. Processes "upstream" of the gasoline-powered vehicle and electric utility plants are then explained in Chapters 6 and 7, respectively. Finally, the processes involved in the manufacture of vehicles and batteries are described in Chapter 8. A series of appendices at the end of the report provide the data and background documents to support the information presented.

2.0 Summary of Total Energy Cycle Results

This section summarizes the total energy cycle results for selected EV and CV scenarios. The scenarios and key assumptions are briefly explained. (Chapters 3 through 8 contain more detail on the scenarios, assumptions and data used in the analysis.) An overview of the energy and environmental results is provided. Then, separate sections describe the specific results for the two metropolitan areas (Houston and Washington, D.C., hereafter referred to as Washington) for which total energy cycle model runs have been completed. A full accounting of the results can be found in Appendix E.

2.1 EVTECA Scenarios and Key Assumptions

A number of factors affect the comparative analysis of the EV and CV energy cycles. Among the most important are:

- market penetration of EVs;
- EV and CV energy efficiency;
- assumptions about how EV batteries are recharged; and
- the processes included in each of the energy cycles (i.e., the "boundary" of the energy cycles examined).

These are discussed below.

2.1.1 Market Penetration and Types of EVs

Two basic EV-market-penetration scenarios were examined in this analysis -- one that assumed moderate penetration of EVs (Low Scenario) and one that assumed fairly high penetration (High Scenario). (These scenarios are explained in more detail in Chapter 3). The sections below focus on the High Scenario, because the results are more interesting and show more dramatic differences between the EV and CV energy cycles. For the High Scenario, we assume implementation of a requirement like the California Zero-Emission-Vehicle (ZEV) mandate in both Texas and Washington. The number of EVs and their vehicle miles traveled (VMT) differ in the two metropolitan areas. In Houston, we project that there will be approximately 200,000 EVs in operation in 2010 and that they will travel 2.6 billion miles in that year. In Washington, we project that 140,000 EVs will travel 1.7 billion miles annually by 2010. These EVs are assumed to replace CVs, and the mileage traveled by CVs, on a one-for-one basis.

Four EV battery types are included in the analysis: lead-acid (Pb-A), sodium sulfur (Na-S), nickel-cadmium (Ni-Cd), and nickel-metal-hydride (Ni-MH). These battery types were chosen after a review of advances in battery technologies and vehicle manufacturer intentions to use certain battery types. By 2010, 56% of EVs in operation in each city are assumed to contain nickel-based batteries, 30% contain Na-S batteries and 14% Pb-A batteries. (See Chapter 4 for additional discussion of the battery types and EV stock estimates.)

2.1.2 EV and CV Energy Efficiency

The total number of EVs in operation, their daily travel, and the energy efficiency of the EVs determines the total daily electricity demand by EVs in a metropolitan area. Estimates of EV energy efficiency are wide ranging. Those used in this analysis are based on an analysis of battery performance characteristics and subsequently the simulated performance of EVs with these batteries on specific driving cycles. The analysis of battery performance examined the performance of existing batteries and accounted for progress in EV battery technology over time. By the latter part of the EVTECA study period, several of the battery types are assumed to meet mid-term goals of the U.S. Advanced Battery Consortium (USABC). For the vehicle simulation, two driving cycles were used: one for vans and one for cars. Both are designed to simulate urban driving.

Base case EV energy efficiencies (without consideration of heating and cooling requirements) are estimated for several time periods: i.e., for model years (MY) up to 2003, MY 2003-2007, and MY 2008-2010. By the latter model years, the base case energy efficiencies of cars range from 0.21 kWh/mile to 0.25 kWh/mile (depending on battery type), minivans range from 0.23 kWh/mile to 0.26 kWh/mile, and full-size vans from 0.38 kWh/mile to 0.43 kWh/mile. Heating and air conditioning requirements vary by metropolitan area. The final EV energy efficiencies estimated in this analysis are presented in Chapter 4.

The fuel economy of the CVs being replaced by EVs is estimated on the same driving cycles. Base case fuel economy is 29 mpg for compacts, 23 mpg for minivans and 15 mpg for full-size vans. Again, the final CV fuel economy estimates incorporate adjustments for heating and air conditioning requirements and are found in Chapter 4.

2.1.3 EV Charging: Utility Simulation Scenarios

Given the electricity demand estimate derived for each EV market penetration scenario, several utility simulation scenarios are used to evaluate the energy use and emissions of EVs. Unless utilities adopt policies designed to encourage EV charging at specific times of the day, EVs will likely be charged when their operators return to their home base at the end of a day. We call such charging "unconstrained charging" and evaluate the resulting incremental power plant fuel use and emissions. Alternatively, utilities may adopt policies such as "time-of-day pricing" of electricity to encourage the charging of EVs in the utilities' off-peak hours. We also evaluate the fuel use and emissions associated with such off-peak EV charging.

In either case, though particularly under "unconstrained charging," the utility analysis indicates that additional power plant capacity will be required as electricity demand increases under the levels of EV charging required by the High Scenario in both Houston and Washington. To maintain utility system reliability, the utility analysis assumes that this new capacity will be provided by either gas-fired combined cycle (CC) or gas-fired combustion turbine (CT) plants.¹ The assumption about which technology is employed for the capacity additions affects the emission results, because the CC and CT designs have different energy efficiencies and environmental characteristics. In addition, the new capacity additions alter the dispatch order within the utility power system thereby changing the incremental power plant fuel use and emissions that can be attributed to EV market penetration. So, we present results for the following four utility simulations scenarios:

¹ The scenarios call for unplanned CC or CT units to come on line to meet incremental demand after all currently planned units are brought on line.

- Unconstrained charging with new capacity² provided by combined cycle units (called the "Unconstrained Charging: Combined Cycle" or UCC scenario);
- Unconstrained charging with new capacity provided by combustion turbine units ("Unconstrained Charging: Combustion Turbine" or UCT scenario);
- Off-peak charging with new capacity³ provided by combined cycle units ("Off-peak Charging, Combined Cycle" or OCC scenario); and
- Off-peak charging with new capacity provided by combustion turbine units ("Off-peak Charging: Combustion Turbine" or OCT scenario).

The utility simulations for the unconstrained charging scenarios were run for all four seasons of the year, while the simulations for the off-peak scenarios were run just for the summer.

2.1.4 Energy Cycle Stages

The EV energy cycle stages included in this analysis are:

- EV battery charging and vehicle operation (these processes consume energy but do not produce emissions);
- power plant operation and electric power distribution for battery charging;
- fuel extraction, processing and transportation required to deliver fuels to the power plants; and
- vehicle and battery manufacture.

The CV energy cycle stages include:

- vehicle operation using reformulated gasoline (RFG);
- RFG production (including production of oxygenates [MTBE for Houston and Washington] and final formulation of RFG in the refinery) and transportation/distribution to these metropolitan areas;
- crude oil extraction, transportation and processing⁴; and
- vehicle manufacture.

² The capacity added by 2010 in the unconstrained scenarios equals 171 MW in Houston and 131 MW in Washington, D.C.

³ Capacity additions by 2010 in the off-peak scenarios equal 0.1 MW in Houston and 53 MW in Washington, D.C.

⁴ Note that some of the results presented below combine production of RFG and crude oil extraction, etc., into a generic "Fuel Extraction and Production" category.

Emissions and energy requirements associated with vehicle manufacture are allocated over the lifetime mileage of vehicles. In other words, the total vehicle manufacture emissions estimates for 2010 are based on the number of miles driven in 2010 by specific vehicle types and the per-mile energy use and emissions associated with manufacturing these vehicle types. For the EVs, we include emissions and energy consumption associated with producing batteries, and the batteries are assumed to be replaced once or twice, depending on the battery type¹, during the course of the vehicle's life.

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 the 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 in the tables and figures in this chapter.

2.1.5 Presentation of Results

A summary of the total energy cycle results, comparing EVs and CVs, is presented in Section 2.2. The specific results for Houston are discussed in Section 2.3 and those for Washington in Section 2.4. Both energy and emissions results are presented. The discussion of emissions focuses on air pollutants (a) because of the continuing importance of transportation to the achievement of NAAQS and (b) because the water pollutant and solid waste characterization in the EVTECA is not as thorough as the air pollutant characterization. The following emissions to the atmosphere are covered:

- carbon dioxide (CO₂)
- methane (CH₄)
- sulfur oxides (SO_x)
- nitrogen oxides (NO_x)
- carbon monoxide (CO)
- total suspended particulate matter (TSP)
- volatile organic compounds (VOC), and
- lead (Pb).

The effects of the variations in time of EV recharge (off-peak versus unconstrained) and type of power plant capacity added (CC versus CT) are included in the results discussion. When appropriate, seasonal emissions values are also discussed. For many pollutants (e.g., VOC), we also discuss their generation within ("in-basin") and outside ("out-of-basin") the boundaries of the two metropolitan areas. Changes in in-basin generation contribute to the attainment or non-attainment by metropolitan areas of the various NAAQS, while out-of-basin generation does not.

¹ Lead-acid batteries are assumed to be replaced twice, and the other battery types are assumed to be replaced once. The emissions associated with production of a battery are distributed over the lifetime of each battery.

2.2 Results: Overview

This study estimated the differences in energy resource consumption and environmental residuals associated with a number of different future scenarios. The principal question addressed in the EVTECA is: How do EVs compare to CVs with regard to energy resource consumption and environmental residuals? The two short sections below summarize the energy and air emissions findings.

2.2.1 Energy Results

Figure 2.1 shows the total energy resource consumption, by fuel type, for all scenarios examined in the EVTECA. The two CV energy cycles (for Houston and Washington) show similar levels of total energy consumption per vehicle mile traveled (approximately 6750-7000 Btu/mile). The CV energy cycles consume considerably more energy resources than any of the EV scenarios: from 15% to 40% more. The EV energy cycles use from 3900 to 5750 Btu/mile.

Of particular interest are the total oil requirements of the two energy cycles. Total oil use is greatly reduced with EVs: over 85% in Houston and 50%-60% in Washington. The reduction is lower in Washington because fuel oil would be used in some of the area's power plants in the future to provide electricity for EVs, while no oil is projected to be used in Houston.

The differences among the per-mile energy resource consumption values for the EV scenarios is caused by a number of factors, but the most important is the variation in the mix of generating units and power plant fuels used in the scenarios. Different units require different fuel input to produce a unit of electricity. For example, in both Houston and Washington, the scenarios that assume CT units are added in response to EV demand use more total energy than those that assume CC units are added to meet this demand. This is to be expected, because CC technology is more energy efficient than CT technology.

As discussed in Section 2.1, the energy results presented here are also highly dependent on the fuel economy of the CVs characterized in this analysis and the energy efficiency of EV operation. The average energy efficiency of the CVs that would be replaced by EVs in 2010 is estimated to be approximately 5500 Btu/mile (summer season) or a fuel economy of 21 mpg. The energy efficiency of EV is about 1150 Btu/mile (at the wall outlet) or 0.34 kWh/mile.

2.2.2 Environmental Results

In some previous analyses of the environmental effects of EVs, analysts have compared the emissions from CV vehicle operation to the emissions from the power plants that charge EVs. In this study, we have examined a wider range of activities related to each of the vehicle types. We include processes involved in producing and distributing RFG, processes upstream of the power plants, and processes supporting vehicle and battery manufacture. The results of this study show that examining only the CV vehicle operation emissions versus the power plant emissions could lead to incorrect conclusions about the relative emissions contributed by CVs and EVs. In the CV energy cycle, the CV operation stage generates the bulk of the CO₂, NO_x, VOC and CO emissions, but vehicle manufacture is the most important contributor to TSP, SO_x, and Pb emissions. Fuel production and ancillary energy production generate the greatest share of CH₄. In the EV cycle, power plants generate the greatest share of CO₂. Vehicle manufacturing generates the greatest amount of TSP, SO_x, CO and Pb. Fuel production generates the greatest amount of CH₄ and VOC. Depending on the EV charging regimen assumed, either power plants or fuel production activities

generate the most NO_x. Therefore, the results of the comparison between EV and CV total energy cycles will vary depending on which pollutant is examined, and will be different from results obtained when just the operation stage of the CV cycle and the power plant stage of the EV cycle are compared.

Selected environmental results for one scenario are shown in Figure 2.2 (see the figures in the rest of this chapter for a more complete picture of the results). The results show that the use of EVs to replace CVs would benefit the environment in the following ways:

- **CO₂:** EVs reduce total CO₂ emissions. The reductions range from 26% to 64% in unconstrained scenarios.
- **VOC:** VOC emissions are dramatically reduced by EVs. Total VOC reductions in the unconstrained scenarios are approximately 90%. In-basin VOC emission reductions range from 98% to 99%.
- **CO:** CO emissions are also dramatically reduced by EVs. Total CO is reduced from 85% to 90%. In-basin CO emissions are reduced from 97% to 99%.
- **NO_x:** All EV scenarios lead to NO_x reductions, both total and in-basin, both annual and summer. However, the results show that the level of reduction can vary greatly between regions and is highly dependent upon the type of EV charging assumed. For Houston, total NO_x is reduced from 7% to 96%, while for Washington NO_x is reduced from 25% to 40%. In Houston, the in-basin NO_x reductions can be as low as 25% and as great as over 100%.² In Washington, the in-basin reductions range from 84% to 97%. Which type of power plant is added under unconstrained charging and whether or not unconstrained charging or off-peak charging is used has substantial effects on the NO_x-related emissions of EVs.

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

- **CH₄:** EVs generally 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 annual increases range from 17% to 47%. However, there may be instances where CH₄ emissions could be roughly similar to those of CVs. In several of the Washington summer scenarios slight reductions (less than 5%) in total CH₄ are achieved.
- **TSP:** TSP emissions will increase with EVs due to vehicle and battery manufacture and power plant operations. The annual increases range from 29% to 64%. However, in-basin TSP emissions are generally lower with EVs. In-basin reductions of up to 75% were estimated. We do not have the data to present PM-10 or PM-2.5 results.
- **SO_x:** SO_x emissions are between eight and eleven times higher in the EV scenarios. The major source of the emissions is not power production, but battery manufacturing (particularly the nickel

²In Houston in selected scenarios, the introduction of EVs results in decreased total NO_x emissions from all power plants serving Houston because the utility company is projected to replace older power plants with highly-efficient, less-polluting new units. This projection affects other emission and energy results in Houston as well (see Section 2.3).

batteries). In-basin SO_x emissions increase with EVs, but the increases are not as great as the total energy cycle increases. Use of unconstrained charging and the addition of CC units in fact can lead to lower in-basin SO_x emissions with EVs in both the Houston and Washington areas.

- **Pb:** Lead emissions increase approximately 400% because of the use of lead-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, though some recycling of battery materials (which was not specifically addressed in this analysis) could occur in-basin.

Whether EVs are charged when their trips end or in the off-peak hours has an effect on the power plant emissions and thus on the total energy cycle emissions. Differences in charging typically affect the magnitude of decreases or increases, as opposed to the direction of those increases or decreases. Similarly, with the unconstrained charging scenarios, the power plant and energy cycle results are affected by whether the capacity added to meet the EV demands is from CC or CT units. Again, it is the magnitude of changes that differs rather than the direction. (This effect is less pronounced when batteries are charged off-peak because fewer new units would be brought on to meet the EV demand for electricity. Therefore the technology used for new units does not as strongly influence the off-peak results.)

While analysis of the Houston and Washington energy cycles indicates that EVs would have similar effects on the vehicle-related emissions of each region, the specific percent increases or decreases vary between the two regions. Given that the market penetration rate of EVs and the vehicle energy efficiencies are the same or very similar, the variations that exist in the emissions results between the two regions must be explained by the types of fuels projected to provide the incremental electricity for EVs. The two regions do vary significantly on this variable. In Houston, nearly all of the electricity provided for EVs in the unconstrained charging scenarios is generated by natural-gas-fired power plants. In the off-peak charging scenarios for Houston, natural gas provides less than half of the electricity for EVs; coal provides the rest (about 55%). In Washington, in both the unconstrained and off-peak charging scenarios, natural gas provides about 40-45% of the electricity and almost all the rest (50% or more) is provided by oil-fired power plants. Coal only generates 4% of the electricity.

Finally, while we reported in-basin results above, these results should be treated with more caution than the total results. In this analysis, we specifically estimated whether the power plants providing the electricity to meet EV demand were in- or out-of-basin. We also reviewed crude refining capacity and oxygenate production capacity for each region to determine the likelihood of in-basin RFG production. Since Houston is a refining center serving the country, our estimation method classified all refining to serve Houston CVs as in-basin. Washington, however, presently has no refineries in-basin, so we classified all refining to serve Washington CVs as out-of-basin. All CV vehicle operation replaced by EVs is expected to be in-basin. However, with respect to vehicle and battery manufacture, production of fuels for use in power plants, and production of ancillary energy, limited analysis suggests that virtually all of this will be out-of-basin. In spite of this limitation, we believe it worthwhile to present the in-basin results to give a sense of their potential direction.

2.3 Houston

Table 2.1 compares energy consumption across the total energy cycles of EVs and CVs in Houston for the summer runs. The table shows the amount of total raw energy resources (crude oil, natural gas, coal) used by various broad segments of the energy cycles. (Where processed resources [such as distillate oil] are

consumed, they are shown in Table 2.1 at their point of production, not at their point of consumption.) Total energy resource consumption by CVs is 6750 Btu/mile traveled. The EV consumption ranges from approximately 3900 to 5750 Btu/mile or a 15%-42% reduction in total energy use. The reduction in total oil use with EVs is even greater: 86%-87%. This is in large part due to the fact that no oil is used to provide electricity to EVs.

Table 2.2 compares EVs and CVs from the point of energy input to the power plant for EVs and refineries for CVs, a more limited comparison, but similar to comparisons frequently made. Again these are the results of summer runs. EVs use 34%-62% less energy. The great reduction in energy use with the UCC scenario is due to the extensive use of new, efficient CC units to meet the electricity demand of the EV scenario. Their addition displaces a number of coal plants in the dispatch order; therefore, the incremental units dispatched to serve EVs have a higher overall energy efficiency in Houston than in the case without EVs. This table also presents the average energy efficiency of the vehicles analyzed in the scenario. The Btu/mile estimates translate to approximately 21 mpg for CVs in 2010 and 0.34 kWh/mile for EVs.

Tables 2.3-2.6 summarize the annual, summer and in-basin air emissions results for the total energy cycles supporting the fleet of 200,000 EVs in Houston, compared to those for the comparable fleet of CVs. The comparison of CV and EV scenarios for each pollutant is discussed in detail below. Note that the bar-chart figures in the sections below show results for summer because we did not generate results for all scenarios on an annual basis. The relative comparisons (i.e., percent differences) among the scenarios for summer usually approximate the annual differences. Some exceptions to that rule are noted in the text below.

Note that all changes associated with EVs are shown with respect to what emissions would have been had an equivalent number of CVs been operating. So, if we say emissions were reduced 98%, we do not intend to impart that total emissions from all sources or total vehicle-related emissions in Houston would be lowered by 98%. Instead, we mean that 98% of the emissions from our CV scenario, which included 200,000 CVs, would be eliminated by replacing the CVs with EVs. The effect on total emissions in Houston would be very low.

2.3.1 CO₂ -- Houston

Compared to the CV scenario, all EV cases show reductions in total-energy-cycle CO₂ emissions. The greatest reduction (64%) occurs in the UCC scenario, both annually and in the summer. In that case, emissions from electric utilities that charge the EVs are quite low because the new CC capacity that is added due to additional electricity demand for EVs is highly efficient and displaces older inefficient power plants in the dispatch order. In all other scenarios (both annual and summer), EVs achieve between a 25% and 32% reduction over CVs. Figure 2.3 compares emissions of CO₂ in the summer for the four utility cases and the CV scenario.

Emissions of CO₂ from the EV cycle are lower than those from the CV cycle for each of the broad segments of the energy cycle except vehicle manufacturing. In that segment, EV CO₂ emissions are nearly double those of CVs because of the large amount of energy-intensive material used in batteries.

A brief discussion of the CO₂ results for each scenario, which are shown in Figure 2.3 and Tables 2.3-2.4, follows in the shaded box.

CO₂ Emissions: Scenario Comparisons for Houston

CV Scenario: The 200,000 CVs (that EVs would replace) generate over 1 million tons of CO₂ annually. The contribution of each energy cycle category to the total CO₂ emissions is as follows:

- 78% of the CO₂ emissions are from vehicle operation
- 11% are from fuel extraction and production
- 7% are from vehicle manufacture
- 4% are from ancillary energy production processes.

These shares vary only slightly in the summer.

EV Unconstrained Charging: Combined Cycle. The greatest source of the CO₂ emissions from the EV energy cycle is power plants (45%), with the next greatest contribution from vehicle manufacture including batteries (40%). The manufacture of batteries for EVs generates more CO₂ emissions than are generated in the manufacture of the rest of the EV (the EV shell). This result is due in part to the fact that we account for EV battery replacement. It is also due to the fact that some of the materials generate a relatively high level of CO₂ emissions per ton used (e.g., nickel). Annually,

- total EV CO₂ emissions are 64% less than total CV CO₂ emissions
- CO₂ emissions from power plants are 79% less than CV operating emissions
- vehicle manufacturing CO₂ emissions are almost double with EVs.

These results vary only slightly in the summer; the overall reduction achieved annually is also 64%.

EV Unconstrained Charging: Combustion Turbine. In this scenario, the annual power plant emissions are much higher, representing 72% of the total EV CO₂ emissions. The power plant emissions are over three times that of the UCC utility simulation scenario because the new CT plants added in this scenario are less efficient than the CC plants, so they consume more energy and do not improve as much upon the older capacity (which is displaced more readily in the dispatch in the UCC scenario). Still, total EV CO₂ emissions are 26% lower than total CV CO₂ emissions. Vehicle manufacturing emissions remain the same as in the UCC scenario. These results vary only slightly in the summer when the overall reduction achieved is 32%.

EV Off-peak Charging: Combined Cycle (summer only). The overall CO₂ reduction achieved in this scenario (25%) is similar to that of the UCT scenario. About 75% of the CO₂ emissions are generated in the power plant, while 16% are from vehicle manufacture.

EV Off-peak Charging: Combustion Turbine (summer only). The results for this scenario are virtually identical to the other off-peak charging scenario: a 25% reduction relative to CVs.

2.3.2 CH₄ -- Houston

Compared to the CV case, all EV scenarios lead to increases in total CH₄ emissions. The increases range from 10% to 57%. The major source of the CH₄ emissions from the EV cycle is the production of fuels (e.g., natural gas) for power plants. Figure 2.4 compares the CH₄ emissions for the summer scenario.

A brief discussion of the CH₄ results for each of the scenarios shown in Figure 2.4 and in Tables 2.3-2.4 follows in the shaded box.

CH₄ Emissions: Scenario Comparisons for Houston

CV Scenario. The 200,000 CVs generate over 2,056 tons of CH₄ annually. A little over 40% is generated in RFG production (extracting and transporting crude oil and producing RFG) and 50% is from the production of ancillary energy. The results are similar on both an annual and summer basis.

EV Unconstrained Charging: Combined Cycle. Annually,

- total CH₄ emissions from the EV cycle are 17% greater than those from the CV cycle
- CH₄ emissions associated with fuel production are 128% higher with EVs
- the CH₄ emissions associated with production of fuels used in power plants makes up 82% of the EV-related CH₄ emissions
- CH₄ emissions from ancillary energy are 64% lower with EVs.

These results vary only slightly in the summer when the overall increase with EVs is 25%.

EV Unconstrained Charging: Combustion Turbine. Annually, total EV CH₄ emissions are 47% greater than total CV CH₄ emissions; and fuel production is again the greatest contributor to the EV-related CH₄ emissions (86%). These results vary only slightly in the summer when the overall increase with EVs is 57%.

EV Off-peak Charging: Combined Cycle (summer only). The overall CH₄ increase with EVs in this scenario is 10%. Again, the major source of the CH₄ is the production of fuel used in the power plants.

EV Off-peak Charging: Combustion Turbine (summer only). The results for this scenario are virtually identical to the other off-peak charging scenario with a 12% increase relative to CVs.

2.3.3 TSP-- Houston

Compared to the CV case, all EV scenarios lead to total increases in TSP emissions. The increases range from 18% to 30%. The major sources of these emissions increases are vehicle and battery manufacture and power plant operation. However, in-basin TSP is generally lower with EVs. The range of reductions is quite dramatic: from a 5% increase to a 75% reduction. Figure 2.5 compares TSP emissions for the summer scenarios. These comparisons are also documented in Tables 2.3-2.6. The shaded box below provides an explanation.

TSP Emissions: Scenario Comparisons for Houston

CV Scenario. The CV energy cycle generates 235 tons of TSP annually.³ The contribution of each energy cycle category to TSP emissions is as follows:

- 68% of the TSP emissions are from vehicle manufacture
- 22% are from vehicle operation
- 5% are from fuel extraction and production
- 5% are from ancillary energy production processes.

25% are in-basin. These shares vary only slightly in the summer.

EV Unconstrained Charging: Combined Cycle. Annually,

- the EV energy cycle emits nearly 30% more total TSP than the CV cycle
- TSP emissions from power plants are 20% higher than CV operating emissions
- in-basin TSP emissions are 5% higher with EVs
- the manufacture of EVs and their batteries results in 49% more TSP than with CVs.

By far, the greatest source of the TSP emissions from the EV energy cycle in this scenario is vehicle and battery manufacture (78%), followed by power plant emissions (20%). These results vary slightly in the summer dispatch results. TSP emissions in the summer are 26% higher with EVs, but in-basin TSP is 5% lower.

³ Note that we present estimates of TSP, although the NAAQS is for PM-10 (particulate matter below 10 microns in diameter) and a new standard for PM-2.5 has been proposed. Data was not readily available to present PM-10 or PM-2.5 estimates in this study.

EV Unconstrained Charging: Combustion Turbine. The total estimates for this scenario are virtually the same as for the UCC utility simulation scenario: 30% more TSP than with CVs. The two EV scenarios differ in terms of the TSP generated by power plants and fuel extraction, but these differences offset each other. In the summer, total TSP is also 30% higher with EVs, but again, there are some differences between the summer and annual results with respect to the contribution of each energy cycle category. In-basin TSP emissions are lower both in the annual and summer scenarios.

EV Off-peak Charging: Combined Cycle (summer only). Compared to the CV case, the overall increase in TSP emissions is 19% in this scenario. A 70% reduction relative to CV operating emissions is achieved by power plants and in-basin emissions are reduced by 74%.

EVs: Off-peak Charging: Combustion Turbine (summer only). The results for this scenario are nearly identical to the other off-peak charging scenario.

2.3.4 SO_x -- Houston

Compared to the CV case, all of the EV scenarios lead to total increases in SO_x emissions. The increases range from 740% to 990%. In-basin increases are not as great and in the UCC scenario, in-basin SO_x emissions are lower with EVs than CVs. The major source of these emissions is battery manufacture. Nickel production, in particular, has a high SO_x emissions rate. The bar chart comparing SO_x emissions among scenarios is found in Figure 2.6. The values are shown in Tables 2.3-2.6, which are explained in the shaded box below.

SO_x Emissions: Scenario Comparison for Houston

CV Scenario. The CV energy cycle in this scenario generates 945 tons of SO_x annually. 27% are in-basin. By far the predominant source of the SO_x emissions is vehicle manufacturing at 54%. These shares vary only slightly in summer.

EV Unconstrained Charging: Combined Cycle. Annually,

- the EV energy cycles emits over eight times as much SO_x as the CV cycle
- the addition of the combined cycle units results in a reduction in SO_x from the baseline utility dispatch because cleaner units are called on to provide the incremental electricity for EVs. As a result, EV power plant SO_x emissions are lower than SO_x emissions from CV vehicle operation
- in-basin SO_x is reduced 300% with EVs
- SO_x emissions from vehicle and battery manufacturing are a major contributor to total EV SO_x emissions.

The manufacture of batteries for EVs generates far more SO_x emissions than are generated in the manufacture of the EV shell. Materials such as nickel have a very high level of SO_x emissions per ton used. The summer results are essentially the same.

EV Unconstrained Charging: Combustion Turbine. The total SO_x estimates for this scenario are slightly higher than the UCC utility simulation scenario. Under this UCT scenario, SO_x emissions would be nearly ten times greater than with CVs. The utility dispatch does not lead to a reduction in power plant SO_x emissions in this scenario. Consequently, SO_x emissions from power plants are almost seven times higher than those from CV operation. In-basin SO_x increases with EVs. The summer results are essentially the same.

EV Off-peak Charging: Combined Cycle (summer only). Total SO_x emissions from the EV cycle in this scenario are about eleven times higher than with those from the CV cycle. The utility dispatch does not lead to a reduction in power plant SO_x emissions in this scenario. Emissions from power plants are about fifteen times higher than those from CV operation. In-basin SO_x is five times higher with EVs.

EV Off-peak Charging: Combustion Turbine (summer only). The results for this scenario are nearly identical to the other off-peak charging scenario.

2.3.5 NO_x -- Houston

All EV scenarios lead to total NO_x decreases relative to the CV scenario (see Figure 2.7 and Tables 2.3-2.6). However, the level of total decrease varies widely: from 7% to 96%. This is also true for the in-basin NO_x which is reduced by 25% to 140%. The large decrease between the CV scenario and the EV UCC scenario (96% on an annual basis) is accompanied by a decline in total NO_x emissions from all power plants serving Houston, but this decline is not seen in the other EV scenarios. Thus, the method by which EVs will be charged (off-peak vs. unconstrained) strongly affects the resulting NO_x emissions (both total and in-basin). The large reduction in NO_x from power plants is slightly offset by a slightly higher level of NO_x from EV vehicle manufacturing, compared to that of CVs. The NO_x emissions from each scenario are further explained in the shaded box below.

NO_x Emissions: Scenario Comparison for Houston

CV Scenario: The CV energy cycle generates 2,832 tons of NO_x annually. The contribution of each energy cycle category to NO_x emissions is as follows:

- 65% of the NO_x emissions are from vehicle operation
- 18% are from fuel extraction and production
- 4% are from vehicle manufacture
- 13% are from ancillary energy production processes.

76% are in-basin. These shares vary only slightly in the summer.

EV Unconstrained Charging: Combined Cycle. Based on the assumptions in this scenario, annually,

- the EV cycle emits 96% fewer total NO_x emissions than the CV cycle
- the addition of the CC units results in a reduction in NO_x from the baseline utility dispatch, because cleaner units are called on to provide the incremental electricity for EVs. As a result, EV power plant NO_x emissions are lower than the NO_x emissions from operation of CVs
- in-basin NO_x emissions are reduced by 140% compared to CVs
- vehicle manufacturing NO_x emissions are twice as high with EVs than with CVs, in part due to the fact that manufacturing of batteries for EVs leads to greater NO_x emissions than does manufacturing the shell of the vehicles.

These results vary slightly in the summer. The EV NO_x emissions are 79% lower.

EV Unconstrained Charging: Combustion Turbine. The total NO_x estimates for this scenario are 15 times higher than the EV UCC scenario. Still, EVs lead to a 40% reduction in total NO_x compared to CVs. In-basin NO_x emissions are 76% lower than with CVs. The results for the summer dispatch are similar, with a total NO_x reduction of 36% and a 78% in-basin reduction.

EV Off-peak-charging: Combined Cycle (summer only). This scenario achieves a small reduction in total NO_x of 7% relative to the CV scenario. Relatively high levels of NO_x are generated by the power plants, so that only an 8% total NO_x reduction is achieved with electricity generation for EVs relative to CV vehicle operation. All of the power plant NO_x emissions are generated within Houston's air basin. However, RFG is produced in the air-basin too, so that the total in-basin reduction with EVs is approximately 25%.

EV Off-peak Charging: Combustion Turbine (summer only). The results for this scenario are nearly identical to the other off-peak charging scenario.

2.3.6 VOC -- Houston

All of the EV scenarios lead to total VOC reductions of approximately 90% and reductions in in-basin emissions of 98 to 99%. The summer scenarios are shown in Figure 2.8. While CVs emit a considerable amount of VOC, power plants and other components of the EV energy cycle have low VOC emissions. From an environmental perspective, the reduction in VOC emissions, which participate in ozone (smog) formation, is one of the most significant benefits of the EV cycle. The annual and summer values for each of the scenarios are shown in Tables 2.3-2.6 and explained below in the shaded box.

VOC Emissions: Scenario Comparison for Houston

CV Scenario: The CV energy cycle generates 2,147 tons of VOC annually. The overwhelming source of these VOC emissions is vehicle operation (94%). 95% are in-basin. These shares vary only slightly in the summer.

EV Unconstrained Charging: Combined Cycle. Annually, under this scenario,

- the EV cycle emits over 90% fewer VOC emissions than the CV cycle
- in-basin VOC emissions are reduced by 98% by use of EVs
- VOC emissions from vehicle manufacture are 50% higher than for CVs
- VOC emissions from fuel production are greater with EVs.

The summer results are almost the same.

EV Unconstrained Charging: Combustion Turbine. The total VOC estimates for this scenario are almost the same as those for the EV UCC scenario. Therefore, this EV scenario also reduces total VOC reductions by 90% and in-basin emissions by 98%. The results for the summer season are similar to the annual results.

EV Off-peak Charging: Combined Cycle (summer only). EVs achieve an 91% total VOC reduction in this scenario and a 99% reduction in VOC in-basin emissions.

EV Off-peak Charging: Combustion Turbine (summer only). The results for this scenario are nearly identical to the other off-peak charging scenario.

2.3.7 CO -- Houston

All EV scenarios lead to total CO reductions of 85%-90% and in-basin emissions reductions of 97% or more (see Fig. 2.9 and Tables 2.3-2.6). CVs are a significant source of CO emissions nationwide, but the power plants associated with the EV energy cycle have low CO emission rates. Because of the larger amount of energy intensive materials used in EV batteries, CO emissions from vehicle and battery manufacturing are higher in all EV cases than in the CV scenario. This effect is more than offset by the much lower emissions from power plants compared to CV operation. Emission values for all scenarios are discussed below in the shaded box.

CO Emissions: Scenario Comparison for Houston

CV Scenario: The CV energy cycle generates 17,826 tons of CO annually in Houston. Similar to the VOC results, the overwhelming source of the CO is from vehicle operation (91%). 91% are in-basin. These shares vary only slightly in the summer.

EV Unconstrained Charging: Combined Cycle. Annually,

- EVs emit 90% less total emissions than CVs
- the addition of the CC units results in a reduction in CO from the baseline utility dispatch because cleaner units are called on to provide the incremental electricity for Evs
- in-basin emissions of CO are negative
- CO emissions from vehicle manufacture are 33% higher with EVs.

These results vary only slightly in the summer.

EV Unconstrained Charging Combustion Turbine: In this scenario, the total CO emissions are higher than in the EV UCC scenario, but remain nearly 90% lower than those in the CV scenario. While the in-basin emissions are not completely eliminated, they are reduced 99%. The summer results are virtually the same.

EV Off-peak Charging Combined Cycle (summer only): The EV energy cycle achieves a 83% total CO reduction in this scenario and a 97% reduction in in-basin CO emissions.

EV Off-peak Charging Combustion Turbine (summer only): The results for this scenario are nearly identical to the other off-peak charging scenario.

2.2.8 Lead -- Houston

We only characterized lead emissions associated with vehicle and battery manufacture. All EVs use more copper (for motors and controllers) than CVs. The production of copper generates considerable lead emissions. The production of lead acid batteries for use in some EVs in the scenarios also generates lead emissions. Thus the EV scenarios lead to an increase of over 400% in lead emissions. (See Tables 2.3-2.4.) All emissions are assumed to be out-of-basin for this analysis.

2.4 Washington

Table 2.7 compares energy consumption across the total energy cycles of EVs and CVs in Washington for the summer runs. Total energy resource consumption by CVs is 7000 Btu/mile traveled, whereas the EV consumption ranges from approximately 4450 to 4900 Btu/mile or 30%-36% less than for CVs. This reduction is within the range estimated for Houston. The reduction in total oil use with EVs is 51%-61%. It is not as great as in Houston because some oil is used in the Washington-area power plants.

Table 2.8 compares EVs and CVs from the point of energy input to the power plant for EVs and refineries for CVs. Again these are the results of summer runs. EVs use 45%-52% less energy, within the range found for Houston. This table also presents the average energy efficiency of the vehicles analyzed in

the scenario. They are essentially the same as in Houston. The Btu/mile estimates translate to approximately 21 mpg for CVs in 2010 and 0.34 kWh/mile for EVs.

Tables 2.9-2.12 summarize the annual, summer, and in-basin air emissions results for the total energy cycles supporting the fleet of 140,000 EVs, compared to those for the comparable fleet of CVs. The general conclusions are the same as those for Houston. The magnitudes of the differences among the scenarios is somewhat different, but the general directions of the changes are most often the same. The comparison of CV and EV scenarios for each of the pollutants is discussed in more detail below.

2.4.1 CO₂ -- Washington

Like the Houston scenarios, all EV scenarios for Washington lead to reductions in total CO₂ emissions, compared to the CV scenario (see Figure 2.10 and Tables 2.9-2.10). These reductions range between 25% and 41%. CO₂ emissions from the EV scenarios are lower than those from the CV scenario for all energy cycle categories except vehicle manufacturing. In that phase, EV CO₂ emissions are nearly double those of CVs.

A brief discussion of the CO₂ results for each of the scenarios follows in the shaded box.

CO₂ Emissions: Scenario Comparisons for Washington

CV Scenario: The CV scenario generates 862,000 tons of CO₂ annually. The contribution of each energy cycle category to the total CO₂ emissions is almost identical to that for Houston, and the seasonal (summer) distribution is also almost the same as the annual.

EV Unconstrained Charging: Combined Cycle: Reductions in Washington are somewhat lower than those in Houston:

- total EV UCC CO₂ emissions are 30% less than CV CO₂ emissions
- CO₂ emissions from the power plants are 35% less than CV operating emissions
- vehicle manufacturing CO₂ emissions are almost double with EVs. As in the Houston energy cycle, the manufacture of batteries for EVs generates more CO₂ emissions than are generated in the manufacture of the rest of the EV (the EV shell).

These results vary slightly in the summer. The overall reduction achieved is 41%.

EV Unconstrained Charging: Combustion Turbine. The annual power plant CO₂ emissions are very similar to those for Houston. The total CO₂ reduction is 26% annually and 35% in the summer. Shares by energy cycle stages are almost the same as in Houston.

EV Off-peak Charging: Combined Cycle (summer only). The overall CO₂ reduction achieved in this scenario is 38%. Almost 70% of the CO₂ emissions in this EV scenario are generated by power plants.

EV Off-peak Charging: Combustion Turbine (summer only). The results for this scenario are almost the same as for the other off-peak charging scenario.

2.4.2 CH₄ -- Washington

In the annual unconstrained charging scenarios, the total energy cycle for EVs produces about 35% more CH₄ emissions than that for CVs (see Table 2.9). However, three of the four EV summer energy cycles (including both of the off-peak scenarios) have slight (no greater than 5%) reductions of CH₄ (see Table 2.10 and Fig. 2.11). The major source of the EV CH₄ emissions is the production of fuels (e.g., natural gas) for power plants.

CH₄ Emissions: Scenario Comparisons for Washington

CV Scenario. The CV energy cycle generates over 1,400 tons of CH₄ annually. A little over 40% is generated in fuel production (RFG and the extraction of oil) and 50% is from the production of ancillary energy. The results are similar on both an annual and summer basis.

EV Unconstrained Charging: Combined Cycle. On an annual basis,

- total CH₄ emissions from the EV cycle under this scenario are 36% greater than total CH₄ emissions in the CV scenario
- CH₄ emissions associated with fuel production are 150% higher with EVs
- the CH₄ emissions associated with production of fuels used in the power plants make up 79% of the EV-related CH₄ emissions
- CH₄ emissions from ancillary energy are 47% lower with EVs.

CH₄ emissions in summer are 1% lower than CH₄ emissions from the CV cycle.

EV Unconstrained Charging: Combustion Turbine. The annual results for this scenario are virtually the same as for the Houston UCT scenario with a 35% increase in total CH₄ emissions with EVs. The summer results show a 5% increase.

EV Off-peak Charging: Combined Cycle (summer only). CH₄ emissions are 5% lower with EVs in this scenario.

EV Off-peak Charging: Combustion Turbine (summer only). CH₄ emissions are 3% lower with EVs in this scenario.

2.4.3 TSP -- Washington

Compared to the CV scenario, all EV scenarios lead to total increases in TSP emissions (see Tables 2.9-2.12 and Fig. 2.12). The annual increase ranges from 53% to 64%. However, as for Houston, in-basin TSP is generally lower with EVs. The annual reductions range from 30% to 61%. Only in the summer OCT scenario are in-basin TSP emissions higher (9%) than those of CVs. The major sources of the TSP emissions are vehicle and battery manufacture and power plant operation. The shaded box below provides more explanation.

TSP Emissions: Scenario Comparisons for Washington

CV Scenario. The CVs energy cycle generates 162 tons of TSP annually. By far, the predominant source of the TSP emissions is vehicle manufacturing: 68%. 21% are in-basin. These shares vary slightly in the summer.

EV Unconstrained Charging: Combined Cycle. On an annual basis,

- EV energy cycle emits over 50% more total TSP than the CV cycles
- TSP emissions from power plants are 133% higher than CV operating emissions
- in-basin TSP emissions are 61% less than with CVs
- the manufacture of EVs and their batteries results in 43% more TSP than the manufacture of CVs.

By far the greatest source of the EV TSP emissions in this scenario is vehicle and battery manufacture (64%), followed by power plant emissions (32%). These results vary slightly in the summer, but the summer results are in the same direction as the annual results.

EV Unconstrained Charging: Combustion Turbine. The results for this scenario are very similar to the UCC scenario: 64% more TSP than in the CV scenario. In the summer dispatch, total TSP is 80% higher with EVs. In-basin TSP emissions are lower both in the annual and summer scenarios.

EV Off-peak Charging: Combined Cycle (summer only). Compared to the CV scenario, the overall increase in TSP emissions is 76% in this off-peak scenario. In-basin emissions are reduced 30%.

EV Off-peak Charging: Combustion Turbine (summer only). Total TSP increases 84% with EVs. In-basin emissions increase 9%.

2.4.4 SO_x -- Washington

Compared to the CV case, all EV scenarios lead to total increases in SO_x emissions. The increases range from 886% to 1020%. The major source of these emissions is battery manufacture. As in the Houston

scenario, in-basin SO_x emission increases are not as great and in the UCC scenario, in-basin SO_x emissions are lower with EVs than CVs. Figure 2.13 and Tables 2.9-2.12 present the results, which are further explained in the shaded box that follows.

SO_x Emissions: Scenario Comparison for Washington

CV Scenario. The CV energy cycle generates 665 tons of SO_x annually. By far the predominant source of the SO_x emissions is in vehicle manufacturing: 53%. 12% are in-basin. These shares vary slightly in the summer.

EV Unconstrained Charging: Combined Cycle. On an annual basis,

- the EV energy cycle emits nearly 10 times as much SO_x as the CV cycle
- SO_x emissions from vehicle and battery manufacturing are the major contributor to total EV SO_x emissions
- in-basin SO_x emissions are 90% lower with EVs.

The summer results are essentially the same; except that the in-basin reduction is 13%.

EV Unconstrained Charging: Combustion Turbine. The total SO_x estimates for this scenario are almost the same as the UCC scenario. Again, SO_x emissions are nearly 10 times greater than with CVs. In this scenario, in-basin SO_x emissions are two to three times higher than with CVs.

EV Off-peak Charging: Combined Cycle (summer only). Total SO_x emissions are about 11 times higher than those of the CV scenario. However, in-basin SO_x emissions are virtually the same as for CVs.

EV Off-peak Charging: Combustion Turbine (summer only). Total SO_x emissions are nearly identical to the other off-peak charging scenario. However, in-basin SO_x emissions are nearly four times as high as those for CVs.

2.4.5 NO_x -- Washington

All EV scenarios lead to total NO_x decreases relative to the CV scenario. The total decreases range from approximately 25% to 40%. The in-basin reductions range from 87% to 97%. The scenarios are presented in Tables 2.9-2.12 and Figure 2.14 and are further discussed below in the shaded box.

NO_x Emissions: Scenario Comparison for Washington

CV Scenario: The CV energy cycle in D.C. would generate 1,931 tons of NO_x annually. The highest contributions (as in Houston) are from vehicle operation (64%) and fuel extraction and production (18%). 64% are in-basin. These shares vary slightly in the summer.

EV Unconstrained Charging: Combined Cycle. In this scenario, on an annual basis:

- the EV cycle emits 41% fewer total NO_x emissions than the CV cycle
- total EV power plant NO_x emissions are 52% lower than NO_x emissions from CV vehicle operation
- only 7% of the power plant emissions are generated in-basin and therefore there is a greater than 97% reduction in NO_x in-basin emissions
- vehicle manufacturing NO_x emissions are double with EVs.

The manufacturing of batteries for EVs leads to greater NO_x emissions than for the rest of the EV shell. These results are virtually the same in the summer, when the total NO_x reduction is 37% lower and in-basin NO_x is reduced 97%.

EV Unconstrained Charging: Combustion Turbine: The total NO_x estimates for this scenario are similar to the UCC scenario, with a total reduction of 35%. In-basin NO_x emissions are 92% lower than with CVs. The results for the summer are similar.

EV Off-peak-charging: Combined Cycle (summer only). This scenario achieves a reduction in total NO_x relative to the CV cycle, of 32%. Again, the in-basin reduction is substantial: 91%.

EV Off-peak Charging: Combustion Turbine (summer only). The results for this scenario are similar to the other off-peak scenario with a 27% reduction in total NO_x and an 84% reduction in in-basin emissions.

2.4.6 VOC -- Washington

All EV scenarios lead to total VOC reductions of over 90 to 99% in-basin emissions. The results are presented in Tables 2.9-2.12 and Figure 2.15. See the shaded box below for more detail.

VOC Emissions: Scenario Comparison for Washington

CV Scenario: In Washington, the CV energy cycle generates 1,300 tons of VOC annually. The overwhelming source of these VOC emissions is vehicle operation (94%). 94% are in-basin. These shares vary slightly in the summer.

EV Unconstrained Charging: Combined Cycle: On an annual basis,

- EVs emit over 90% less total VOC emissions than CVs
- in-basin VOC emissions are reduced by 99%

- VOC emissions from vehicle manufacture are approximately 40% higher than for CVs
- VOC emissions from fuel production are over 60% greater with EVs.

The summer results are quite similar.

EV Unconstrained Charging Combustion Turbine: The annual VOC results for this scenario are virtually the same as for the UCC scenario. The summer and in-basin results are virtually the same as for the UCC scenario.

EV Off-peak Charging Combined Cycle (summer only): The EV energy cycle achieves a 91% total VOC reduction in this scenario and a 99% reduction in in-basin VOC emissions.

EV Off-peak Charging Combustion Turbine (summer only): The results for this scenario are the same as for the other off-peak scenario.

2.4.7 CO -- Washington

All EV scenarios lead to total CO reductions of 85%-90%, with 99% or greater reductions for in-basin emissions. CO emissions from vehicle manufacturing increase with EVs. Tables 2.9-2.12 and Figure 2.16 present the results, which are also discussed in the shaded box below.

CO Emissions: Scenario Comparison for Washington

CV Scenario: The CV energy cycle generates nearly 14,000 tons of CO annually. As in the Houston scenarios, the overwhelming source of the CO is from vehicle operation (92%). 92% are in-basin. These shares vary slightly in the summer.

EV Unconstrained Charging: Combined Cycle. On an annual basis,

- EVs emit 90% less total CO emissions than CVs
- in-basin emissions of CO are nearly 100% lower than with CVs
- CO emissions from vehicle manufacture are 27% higher with EVs.

These results vary slightly in the summer, when there is an 85% reduction in total CO emissions.

EV Unconstrained Charging: Combustion Turbine. In this scenario, the EV total CO emissions are very similar to those of the UCC scenario, leading to a 90% reduction in total CO. Again, the in-basin emissions are reduced nearly 100%.

EV Off-peak Charging: Combined Cycle (summer only). EVs achieve an 85% total CO reduction in this scenario and a 99% reduction in CO in-basin emissions.

EV Off-peak Charging: Combustion Turbine (summer only). The results for this scenario are nearly identical to the other off-peak scenario.

2.4.8 Lead -- Washington

As in the Houston analysis, the EV scenarios lead to an over 400% increase in lead emissions. Again, they are all assumed to be out-of-basin.

Table 2.1 Total Energy Use: Houston

Process/ Segment	Fuel Type	CV		EV Unconstrained CC		EV Unconstrained CT		EV Offpeak CC		EV Offpeak CT	
		MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi
Power Production and Fuel Extraction/Processing/Transportation											
	Gas	0	0	2,513,163	3,571	2,759,082	3,920	1,321,833	1,878	1,366,713	1,942
	Oil	0	0	0	0	0	0	0	0	0	0
	Coal	0	0	-548,064	-779	447,034	635	1,456,408	2,069	1,422,949	2,022
	Total	0	0	1,965,099	2,792	3,206,116	4,555	2,778,242	3,947	2,789,662	3,963
CV Operation and RFG Production											
	Gas	739,580	1,051	0	0	0	0	0	0	0	0
	Oil	3,481,798	4,947	0	0	0	0	0	0	0	0
	Coal	0	0	0	0	0	0	0	0	0	0
	Total	4,221,378	5,998	0	0	0	0	0	0	0	0
Vehicle/Battery Production											
	Gas	78,086	111	99,066	141	99,066	141	99,066	141	99,066	141
	Oil	0	0	0	0	0	0	0	0	0	0
	Coal	122,256	174	142,694	203	142,694	203	142,694	203	142,694	203
	Total	200,343	285	241,761	343	241,761	343	241,761	343	241,761	343
Ancillary Energy											
	Gas	174,159	247	53,810	76	57,419	82	57,267	81	57,265	81
	Oil	71,777	102	448,129	637	496,561	705	483,359	687	483,695	687
	Coal	83,096	118	45,256	64	49,145	70	50,852	72	50,792	72
	Total	329,031	467	547,194	777	603,124	857	591,478	840	591,752	841
SubTotal											
	Gas	991,825	1,409	2,666,039	3,788	2,915,568	4,142	1,478,166	2,100	1,523,044	2,164
	Oil	3,553,575	5,049	448,129	637	496,561	705	483,359	687	483,695	687
	Coal	205,352	292	-360,114	-512	638,873	908	1,649,955	2,344	1,616,436	2,297
	Total	4,750,752	6,750	2,754,054	3,913	4,051,001	5,756	3,611,481	5,131	3,623,175	5,148

Total miles of travel: 704 Million

MBtu = Million Btu

Table 2.2 Vehicle, Refinery, and Power Plant Fuel Use: Houston

Process/ Segment	Fuel Type	CV		EV Unconstrained CC		EV Unconstrained CT		EV Offpeak CC		EV Offpeak CT	
		MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi
Fuel for RFG and Power Production											
	Natural Gas	739,580	1,051	2,133,279	3,031	2,342,026	3,327	1,122,028	1,594	1,160,124	1,648
	Crude Oil	3,481,798	4,947	0	0	0	0	0	0	0	0
	Subbituminous	0	0	-548,064	-779	447,034	635	1,456,408	2,069	1,422,949	2,022
	Total	4,221,378	5,998	1,585,215	2,252	2,789,059	3,963	2,578,436	3,663	2,583,073	3,670
RFG and Electricity Consumption in Vehicles											
	RFG	3,809,687	5,413	0	0	0	0	0	0	0	0
	Electricity from Coal	0	0	-179,419	-255	145,917	207	475,459	676	464,184	659
	Electricity from Gas	0	0	1,028,445	1,461	703,110	999	373,568	531	384,842	547
	Total Electricity	0	0	849,026	1,206	849,026	1,206	849,026	1,206	849,026	1,206
	Electricity Into Vehicles *	0	0	806,575	1,146	806,575	1,146	806,575	1,146	806,575	1,146
Conversion Efficiency by Fuel Type											
	RFG	90.25%									
	Coal			32.74%		32.64%		32.65%		32.62%	
	Gas			48.21%		30.02%		33.29%		33.17%	
	Total	90.25%		53.56%		30.44%		32.93%		32.87%	

Gross Conversion
Efficiency **

90.25% 53.56% 30.44% 32.93% 32.87%

Net Delivery
Efficiency **

90.25% 50.88% 28.92% 31.28% 31.23%

Total miles of travel: 704 Million
MBtu = Million Btu

* Excludes transmission and distribution losses.

** "Gross Conversion Efficiency" for electricity is the efficiency of electricity generation and "Net Delivery Efficiency" is the efficiency of electricity generation and transportation and distribution to the end user.

Table 2.3 Annual Emissions in Houston -- High 2010 Scenario

Category	CV Scenario (annual tons)	Share	EV UCC Scenario (annual tons)	Share	Percent Reduction	EV UCT Scenario (annual tons)	Share	Percent Reduction
CO₂ - TOTAL	1,230,809	1.000	437,577	1.000	64.4%	912,912	1.000	25.8%
CV/Power Plant Operation	954,760	0.776	196,913	0.450	79.4%	653,233	0.716	31.6%
Fuel Production	132,651	0.108	25,641	0.059	80.7%	40,612	0.044	69.4%
Vehicle Manufacture	88,300	0.072	172,849	0.395	-95.8%	172,849	0.189	-95.8%
Ancillary Energy	55,097	0.045	42,174	0.096	23.5%	46,218	0.051	16.1%
CH₄ - TOTAL	2,056	1.000	2,412	1.000	-17.3%	3,020	1.000	-46.9%
CV/Power Plant Operation	148	0.072	56	0.023	62.1%	36	0.012	75.7%
Fuel Production	866	0.421	1,976	0.819	-128.3%	2,585	0.856	-198.7%
Vehicle Manufacture	7	0.003	11	0.005	-68.2%	11	0.004	-68.2%
Ancillary Energy	1,037	0.504	369	0.153	64.4%	389	0.129	62.5%
TSP - TOTAL	235	1.000	303	1.000	-28.6%	303	1.000	-28.8%
CV/Power Plant Operation	51	0.217	62	0.203	-20.6%	46	0.151	10.0%
Fuel Production	13	0.054	(5)	-0.015	136.0%	11	0.036	14.8%
Vehicle Manufacture	159	0.676	236	0.781	-48.6%	236	0.780	-48.6%
Ancillary Energy	13	0.054	9	0.031	25.7%	10	0.033	19.7%
SO_x - TOTAL	945	1.000	8,290	1.000	-777.0%	9,629	1.000	-918.6%
CV/Power Plant Operation	110	0.116	(545)	-0.066	597.2%	752	0.078	-586.5%
Fuel Production	184	0.194	44	0.005	76.2%	75	0.008	58.9%
Vehicle Manufacture	509	0.538	8,694	1.049	-1609.2%	8,694	0.903	-1609.2%
Ancillary Energy	143	0.152	98	0.012	32.0%	107	0.011	25.5%
NO_x - TOTAL	2,832	1.000	112	1.000	96.0%	1,696	1.000	40.1%
CV/Power Plant Operation	1,833	0.648	(872)	-7.766	147.6%	520	0.307	71.6%
Fuel Production	497	0.175	555	4.941	-11.7%	733	0.432	-47.5%
Vehicle Manufacture	118	0.042	252	2.242	-113.3%	252	0.148	-113.3%
Ancillary Energy	383	0.135	178	1.583	53.6%	191	0.113	50.2%
VOC - TOTAL	2,147	1.000	198	1.000	90.8%	225	1.000	89.5%
CV/Power Plant Operation	2,023	0.942	34	0.170	98.3%	32	0.143	98.4%
Fuel Production	49	0.023	127	0.641	-157.5%	154	0.686	-214.1%
Vehicle Manufacture	11	0.005	17	0.085	-46.4%	17	0.075	-46.4%
Ancillary Energy	63	0.029	21	0.104	67.3%	22	0.096	65.5%
CO - TOTAL	17,826	1.000	1,696	1.000	90.5%	2,257	1.000	87.3%
CV/Power Plant Operation	16,242	0.911	(345)	-0.204	102.1%	166	0.074	99.0%
Fuel Production	82	0.005	103	0.061	-25.3%	151	0.067	-84.4%
Vehicle Manufacture	1,435	0.081	1,909	1.126	-33.0%	1,909	0.846	-33.0%
Ancillary Energy	66	0.004	28	0.017	57.0%	30	0.013	54.4%
Pb - TOTAL	0.09	1.000	0.46	1.000	-411.1%	0.46	1.000	-411.1%
CV/Power Plant Operation	0.00	0.000	0.00	0.000	-	0.00	0.000	-
Fuel Production	0.00	0.000	0.00	0.000	-	0.00	0.000	-
Vehicle Manufacture	0.09	1.000	0.46	1.000	-411.1%	0.46	1.000	-411.1%
Ancillary Energy	0.00	0.000	0.00	0.000	-	0.00	0.000	-

Note: Values in parentheses are negative values.

Table 2.4 Summer Emissions in Houston -- High 2010 Scenario

Category	CV Scenario (summer tons)	Share	EV UCC Scenario (summer tons)	Share	Percent Reduction	EV UCT Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CC Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CT Scenario (summer tons)	Share	Percent Reduction
CO₂ - TOTAL	381,934	1.000	138,606	1.000	63.7%	258,049	1.000	32.4%	286,010	1.000	25.1%	284,863	1.000	25.4%
CV/Power Plant Operation	300,233	0.786	70,999	0.512	76.4%	185,162	0.718	38.3%	215,650	0.754	28.2%	214,432	0.753	28.6%
Fuel Production	41,310	0.108	8,532	0.062	79.3%	12,778	0.050	69.1%	10,163	0.036	75.4%	10,238	0.036	75.2%
Vehicle Manufacture	24,175	0.063	47,325	0.341	-95.8%	47,325	0.183	-95.8%	47,325	0.165	-95.8%	47,325	0.166	-95.8%
Ancillary Energy	16,215	0.042	11,750	0.085	27.5%	12,784	0.050	21.2%	12,873	0.045	20.6%	12,869	0.045	20.6%
Share Summer is of total	0.31		0.32			0.28								
CH₄ - TOTAL	617	1.000	769	1.000	-24.6%	968	1.000	-56.7%	681	1.000	-10.3%	690	1.000	-11.7%
CV/Power Plant Operation	34	0.056	17	0.022	51.6%	12	0.012	64.8%	7	0.011	78.2%	8	0.011	77.8%
Fuel Production	270	0.437	647	0.842	-140.1%	845	0.873	-213.5%	564	0.828	-109.2%	572	0.830	-112.4%
Vehicle Manufacture	2	0.003	3	0.004	-68.5%	3	0.003	-68.5%	3	0.004	-68.5%	3	0.004	-68.5%
Ancillary Energy	312	0.505	102	0.133	67.2%	108	0.111	65.5%	107	0.157	65.8%	107	0.155	65.8%
Share Summer is of total	0.30		0.32			0.32								
TSP - TOTAL	65	1.000	82	1.000	-25.6%	85	1.000	-30.2%	77	1.000	-18.6%	77	1.000	-18.3%
CV/Power Plant Operation	14	0.215	16	0.191	-11.8%	15	0.176	-6.9%	4	0.055	69.9%	4	0.054	70.3%
Fuel Production	4	0.061	(1)	-0.014	129.9%	2	0.028	40.4%	5	0.070	-37.8%	5	0.069	-35.3%
Vehicle Manufacture	44	0.669	65	0.792	-48.6%	65	0.763	-48.6%	65	0.838	-48.6%	65	0.840	-48.6%
Ancillary Energy	4	0.056	3	0.032	29.0%	3	0.033	23.8%	3	0.037	22.4%	3	0.037	22.7%
Share Summer is of total	0.28		0.27											
SO_x - TOTAL	273	1.000	2,291	1.000	-740.3%	2,608	0.271	-856.5%	2,957	1.000	-984.3%	2,982	1.000	-993.5%
CV/Power Plant Operation	34	0.125	(131)	-0.057	483.4%	175	0.018	-412.7%	527	0.178	-1443.0%	552	0.185	-1515.9%
Fuel Production	57	0.210	15	0.006	74.4%	23	0.002	59.1%	20	0.007	65.3%	20	0.007	65.2%
Vehicle Manufacture	139	0.511	2,380	1.039	-1609.2%	2,380	0.247	-1609.2%	2,380	0.805	-1609.2%	2,380	0.798	-1609.2%
Ancillary Energy	42	0.154	27	0.012	35.6%	29	0.003	30.1%	30	0.010	29.0%	30	0.010	29.0%
Share Summer is of total	0.29		0.28			0.27								

Note: Value in parentheses are negative values.

Table 2.4 Summer Emissions in Houston -- High 2010 Scenario (cont'd.)

Category	CV Scenario (summer tons)	Share	EV UCC Scenario (summer tons)	Share	Percent Reduction	EV UCT Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CC Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CT Scenario (summer tons)	Share	Percent Reduction
NO_x - TOTAL	750	1.000	156	1.000	79.2%	481	1.000	35.8%	694	1.000	7.4%	700	1.000	6.6%
CV/Power Plant Operation	448	0.597	(144)	-0.922	132.2%	120	0.250	73.1%	411	0.592	8.2%	415	0.593	7.4%
Fuel Production	155	0.206	182	1.165	-17.6%	239	0.497	-54.6%	161	0.232	-4.2%	164	0.234	-5.7%
Vehicle Manufacture	32	0.043	69	0.441	-113.3%	69	0.143	-113.3%	69	0.099	-113.3%	69	0.098	-113.3%
Ancillary Energy	115	0.153	49	0.316	57.1%	53	0.110	54.2%	53	0.076	54.1%	53	0.075	54.1%
Share Summer is of total	0.26		1.39			0.28								
VOC - TOTAL	509	1.000	60	1.000	88.2%	72	1.000	85.9%	47	1.000	90.7%	48	1.000	90.6%
CV/Power Plant Operation	471	0.926	9	0.143	98.2%	10	0.138	97.9%	5	0.109	98.9%	5	0.106	98.9%
Fuel Production	15	0.030	41	0.686	-169.4%	51	0.714	-234.8%	32	0.668	-106.6%	32	0.673	-110.5%
Vehicle Manufacture	3	0.006	5	0.076	-46.0%	5	0.064	-46.0%	5	0.097	-46.0%	5	0.096	-46.0%
Ancillary Energy	19	0.038	6	0.095	70.2%	6	0.084	68.7%	6	0.126	68.9%	6	0.124	68.9%
Share Summer is of total	0.24		0.30			0.32								
CO - TOTAL	3,915	1.000	502	1.000	87.2%	610	1.000	84.4%	677	1.000	82.7%	660	1.000	83.1%
CV/Power Plant Operation	3,476	0.888	(63)	-0.125	101.8%	31	0.050	99.1%	110	0.162	96.8%	93	0.140	97.3%
Fuel Production	26	0.007	34	0.068	-33.0%	48	0.079	-88.9%	36	0.053	-41.3%	36	0.055	-42.7%
Vehicle Manufacture	393	0.100	523	1.042	-33.0%	523	0.857	-33.0%	523	0.772	-33.0%	523	0.792	-33.0%
Ancillary Energy	20	0.005	8	0.016	60.4%	8	0.014	58.1%	8	0.012	58.2%	8	0.013	58.2%
Share Summer is of total	0.22		0.3			0.27								
Pb - TOTAL	0.020	1.000	0.12	1.000	-500.0%	0.12	1.000	-500.0%	0.12	1.000	-500.0%	0.12	1.000	-500.0%
CV/Power Plant Operation	0.000	0.000	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-
Fuel Production	0.000	0.000	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-
Vehicle Manufacture	0.020	1.000	0.12	1.000	-500.0%	0.12	1.000	-500.0%	0.12	1.000	-500.0%	0.12	1.000	-500.0%
Ancillary Energy	0.000	0.000	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-
Share Summer is of total	0.22		0.26			0.26								

Note: Value in parentheses are negative values.

Table 2.5 Annual In-Basin Emissions in Houston -- High 2010 Scenario

Category	CV Scenario (annual tons)	Share	EV UCC Scenario (annual tons)	Share	Percent Reduction	EV UCT Scenario (annual tons)	Share	Percent Reduction
TSP - TOTAL	59	0.250	62	0.204	-5.1%	46	0.152	21.8%
CV/Power Plant Operation	51	1.000	62	1.003	-21.0%	46	1.000	9.9%
Fuel Production	8	0.613	0	0.000	100.0%	0	0.000	100.0%
Vehicle Manufacture	0	0.000	0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000	
SO_x - TOTAL	259	0.274	(539)	-0.065	308.4%	753	0.078	-191.2%
CV/Power Plant Operation	110	1.000	(539)	0.989	591.7%	753	1.001	-587.0%
Fuel Production	149	0.811	0	0.000	100.0%	0	0.000	100.0%
Vehicle Manufacture	0	0.000	0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000	
NO_x - TOTAL	2,159	0.762	(865)	-7.704	140.1%	521	0.307	75.9%
CV/Power Plant Operation	1,833	1.000	(865)	0.992	147.2%	521	1.001	71.6%
Fuel Production	325	0.654	0	0.000	100.0%	0	0.000	100.0%
Vehicle Manufacture	0	0.000	0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000	
VOC - TOTAL	2,040	0.950	34	0.170	98.4%	32	0.143	98.4%
CV/Power Plant Operation	2,023	1.000	34	1.002	98.3%	32	1.000	98.4%
Fuel Production	17	0.351	0	0.000	100.0%	0	0.000	100.0%
Vehicle Manufacture	0	0.000	0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000	
CO - TOTAL	16,288	0.914	(345)	-0.203	102.1%	166	0.074	99.0%
CV/Power Plant Operation	16,242	1.000	(345)	0.998	102.1%	166	1.000	99.0%
Fuel Production	45	0.554	0	0.000	100.0%	0	0.000	100.0%
Vehicle Manufacture	0	0.000	0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000	

Note: Value in parentheses are negative values.

Table 2.6 Summer In-Basin Emissions in Houston -- High 2010 Scenario

Category	CV Scenario (summer tons)	Share	EV UCC Scenario (summer tons)	Share	Percent Reduction	EV UCT Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CC Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CT Scenario (summer tons)
TSP - TOTAL	16	0.252	16	0.191	4.6%	15	0.176	8.8%	4	0.055	74.3%	4
CV/Power Plant Operation	14	1.000	16	1.000	-11.8%	15	1.000	-6.9%	4	1.000	69.9%	4
Fuel Production	2	0.614	0	0.000	100.0%	0	0.000	100.0%	0	0.000	100.0%	0
Vehicle Manufacture	0	0.000	0	0.000		0	0.000		0	0.000		0
Ancillary Energy	0	0.000	0	0.000		0	0.000		0	0.000		0
SO_x - TOTAL	81	0.295	(131)	-0.057	262.5%	175	0.067	-117.2%	527	0.178	-554.0%	552
CV/Power Plant Operation	34	1.000	(131)	1.000	483.4%	175	1.000	-412.5%	527	1.000	-1443.0%	552
Fuel Production	46	0.811	0	0.000	100.0%	0	0.000	100.0%	0	0.000	100.0%	0
Vehicle Manufacture	0	0.000	0	0.000		0	0.000		0	0.000		0
Ancillary Energy	0	0.000	0	0.000		0	0.000		0	0.000		0
NO_x - TOTAL	549	0.732	(144)	-0.922	126.2%	120	0.250	78.1%	411	0.592	25.1%	415
CV/Power Plant Operation	448	1.000	(144)	1.000	132.2%	120	1.000	73.1%	411	1.000	8.2%	415
Fuel Production	101	0.654	0	0.000	100.0%	0	0.000	100.0%	0	0.000	100.0%	0
Vehicle Manufacture	0	0.000	0	0.000		0	0.000		0	0.000		0
Ancillary Energy	0	0.000	0	0.000		0	0.000		0	0.000		0
VOC - TOTAL	477	0.937	9	0.143	98.2%	10	0.138	97.9%	5	0.109	98.9%	5
CV/Power Plant Operation	471	1.000	9	1.000	98.2%	10	1.000	97.9%	5	1.000	98.9%	5
Fuel Production	5	0.351	0	0.000	100.0%	0	0.000	100.0%	0	0.000	100.0%	0
Vehicle Manufacture	0	0.000	0	0.000		0	0.000		0	0.000		0
Ancillary Energy	0	0.000	0	0.000		0	0.000		0	0.000		0
CO - TOTAL	3,490	0.892	(63)	-0.125	101.8%	31	0.050	99.1%	110	0.162	96.8%	93
CV/Power Plant Operation	3,476	1.000	(63)	1.000	101.8%	31	1.000	99.1%	110	1.000	96.8%	93
Fuel Production	14	0.554	0	0.000	100.0%	0	0.000	100.0%	0	0.000	100.0%	0
Vehicle Manufacture	0	0.000	0	0.000		0	0.000		0	0.000		0
Ancillary Energy	0	0.000	0	0.000		0	0.000		0	0.000		0

Note: Value in parentheses are negative values.

Table 2.7 Energy Use in Washington, D.C. Scenario

Process/ Segment	Fuel Type	CV		EV Unconstrained CC		EV Unconstrained CT		EV Offpeak CC		EV Offpeak CT	
		MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi
Power Production and Fuel Extraction/Processing/Transportation											
	Gas	0	0	849,546	1,800	909,214	1,926	753,676	1,597	754,920	1,599
	Oil	0	0	684,078	1,449	829,173	1,757	833,188	1,765	941,774	1,995
	Coal	0	0	55,333	117	55,371	117	63,983	136	63,983	136
	Total	0	0	1,588,957	3,366	1,793,758	3,800	1,650,847	3,498	1,760,678	3,730
CV Operation and RFG Production											
	Gas	515,581	1,092	0	0	0	0	0	0	0	0
	Oil	2,427,255	5,143	0	0	0	0	0	0	0	0
	Coal	0	0	0	0	0	0	0	0	0	0
	Total	2,942,836	6,235	0	0	0	0	0	0	0	0
Vehicle/Battery Production											
	Gas	54,407	115	65,921	140	65,921	140	65,921	140	65,921	140
	Oil	0	0	0	0	0	0	0	0	0	0
	Coal	85,612	181	95,326	202	95,326	202	95,326	202	95,326	202
	Total	140,019	297	161,247	342	161,247	342	161,247	342	161,247	342
Ancillary Energy											
	Gas	121,039	256	36,137	77	36,530	77	36,218	77	36,413	77
	Oil	43,036	91	278,625	590	281,270	596	275,708	584	276,083	585
	Coal	57,881	123	34,503	73	35,365	75	35,260	75	35,847	76
	Total	221,955	470	349,265	740	353,164	748	347,186	736	348,343	738
SubTotal											
	Gas	691,027	1,464	951,605	2,016	1,011,665	2,143	855,815	1,813	857,255	1,816
	Oil	2,470,290	5,234	962,703	2,040	1,110,443	2,353	1,108,896	2,349	1,217,857	2,580
	Coal	143,493	304	185,162	392	186,061	394	194,569	412	195,156	413
	Total	3,304,810	7,002	2,099,469	4,448	2,308,169	4,890	2,159,281	4,575	2,270,268	4,810

Total miles of travel: 472 Million
MBtu = Million Btu

Table 2.8 Vehicle, Refinery, and Power Plant Fuel Use in Washington, D.C.

Process/ Segment	Fuel Type	CV		EV Unconstrained CC		EV Unconstrained CT		EV Offpeak CC		EV Offpeak CT	
		MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi	MBtu	Btu/Mi
Fuel for RFG and Power Production	Natural Gas	515,581	1,092	691,854	1,466	736,293	1,560	604,094	1,280	600,503	1,272
	Fuel Oil 1	0	0	-16	0	2	0	-4	0	-4	0
	Fuel Oil 2/4	0	0	-30,328	-64	-16,266	-34	27,591	58	37,180	79
	Fuel Oil 6/7	0	0	710,693	1,506	840,919	1,782	801,059	1,697	899,464	1,906
	Crude Oil	2,427,255	5,143	0	0	0	0	0	0	0	0
	Bit. Coal	0	0	55,333	117	55,371	117	63,983	136	63,983	136
	Total	2,942,836	6,235	1,427,536	3,024	1,616,317	3,424	1,496,723	3,171	1,601,126	3,392
RFG and Electricity Consumption in Vehicles	RFG	2,655,836	5,627	0	0	0	0	0	0	0	0
	Electricity from Coal	0	0	18,988	40	19,001	40	21,933	46	21,933	46
	Electricity from Gas	0	0	324,051	687	275,231	583	271,692	576	235,053	498
	Electricity from Oil 1	0	0	-3	0	0	0	-1	0	-1	0
	Electricity from Oil 2/4	0	0	-9,162	-19	-4,541	-10	8,408	18	11,661	25
	Electricity from Oil 6/7	0	0	245,825	521	290,009	614	277,668	588	311,053	659
	Total Electricity	0	0	579,700	1,228	579,700	1,228	579,700	1,228	579,700	1,228
	Electricity Into Vehicles *	0	0	550,715	1,167	550,715	1,167	550,715	1,167	550,715	1,167
Conversion Efficiency by Fuel Type	RFG	90.25%									
	Coal			34.32%		34.32%		34.28%		34.28%	
	Gas			46.84%		37.38%		44.98%		39.14%	
	Oil 1			17.35%		17.40%		17.34%		17.34%	
	Oil 2/4			30.21%		27.91%		30.47%		31.36%	
	Oil 6/7			34.59%		34.49%		34.66%		34.58%	
	Total	90.25%		40.61%		35.87%		38.73%		36.21%	

Gross Conversion
Efficiency **

90.25% 40.61% 35.87% 38.73% 36.21%

Net Delivery
Efficiency **

90.25% 38.58% 34.07% 36.79% 34.40%

Total miles of travel: 472 Million
MBtu - Million Btu

* Excludes transmission and distribution losses.

** "Gross Conversion Efficiency" for electricity is the efficiency of electricity generation and "Net Delivery Efficiency" is the efficiency of electricity generation and transportation and distribution to the end user.

Table 2.9 Annual Emissions in Washington, D.C. -- High 2010 Scenario

Category	CV Scenario (annual tons)	Share	EV UCC Scenario (annual tons)	Share	Percent Reduction	EV UCT Scenario (annual tons)	Share	Percent Reduction
CO₂ - TOTAL	861,757	1.000	604,243	1.000	29.9%	643,046	1.000	25.4%
CV/Power Plant Operation	667,516	0.775	435,711	0.721	34.7%	469,530	0.730	29.7%
Fuel Production	94,403	0.110	22,450	0.037	76.2%	27,144	0.042	71.2%
Vehicle Manufacture	61,612	0.071	114,806	0.190	-86.3%	114,806	0.179	-86.3%
Ancillary Energy	38,226	0.044	31,276	0.052	18.2%	31,566	0.049	17.4%
CH₄ - TOTAL	1,416	1.000	1,920	1.000	-35.5%	1,907	1.000	-34.6%
CV/Power Plant Operation	89	0.062	19	0.010	78.6%	17	0.009	81.3%
Fuel Production	607	0.429	1,516	0.790	-149.7%	1,505	0.789	-147.8%
Vehicle Manufacture	5	0.003	7	0.004	-60.2%	7	0.004	-60.2%
Ancillary Energy	716	0.506	377	0.197	47.3%	378	0.198	47.2%
TSP - TOTAL	162	1.000	249	1.000	-53.1%	266	1.000	-63.6%
CV/Power Plant Operation	34	0.211	80	0.320	-132.9%	96	0.362	-181.1%
Fuel Production	9	0.057	4	0.017	54.8%	5	0.018	49.1%
Vehicle Manufacture	110	0.679	158	0.635	-43.2%	158	0.594	-43.2%
Ancillary Energy	9	0.054	7	0.028	20.7%	7	0.026	19.6%
SO_x - TOTAL	665	1.000	6,557	1.000	-886.0%	6,900	1.000	-937.6%
CV/Power Plant Operation	77	0.116	842	0.128	-994.2%	1,177	0.171	-1430.1%
Fuel Production	136	0.204	41	0.006	69.8%	48	0.007	64.7%
Vehicle Manufacture	353	0.530	5,599	0.854	-1487.5%	5,599	0.811	-1487.5%
Ancillary Energy	100	0.150	75	0.011	24.6%	76	0.011	23.6%
NO_x - TOTAL	1,931	1.000	1,148	1.000	40.6%	1,285	1.000	33.4%
CV/Power Plant Operation	1,235	0.640	590	0.514	52.2%	722	0.562	41.5%
Fuel Production	347	0.180	267	0.233	23.0%	272	0.212	21.7%
Vehicle Manufacture	82	0.042	167	0.146	-103.7%	167	0.130	-103.7%
Ancillary Energy	267	0.138	123	0.107	53.9%	124	0.096	53.6%
VOC - TOTAL	1,297	1.000	94	1.000	92.8%	95	1.000	92.7%
CV/Power Plant Operation	1,212	0.935	15	0.158	98.8%	17	0.176	98.6%
Fuel Production	32	0.025	54	0.576	-66.5%	53	0.560	-63.3%
Vehicle Manufacture	8	0.006	11	0.120	-41.2%	11	0.119	-41.2%
Ancillary Energy	44	0.034	14	0.146	68.8%	14	0.145	68.8%
CO - TOTAL	13,876	1.000	1,435	1.000	89.7%	1,453	1.000	89.5%
CV/Power Plant Operation	12,776	0.921	65	0.045	99.5%	83	0.057	99.3%
Fuel Production	47	0.003	69	0.048	-47.3%	69	0.047	-47.5%
Vehicle Manufacture	1,007	0.073	1,282	0.894	-27.4%	1,282	0.882	-27.4%
Ancillary Energy	46	0.003	19	0.013	59.0%	19	0.013	58.9%
Pb - TOTAL	0.06	1.000	0.37	1.000	-485.7%	0.37	1.000	-485.7%
CV/Power Plant Operation	0.00	0.000	0.00	0.000	-	0.00	0.000	-
Fuel Production	0.00	0.000	0.00	0.000	-	0.00	0.000	-
Vehicle Manufacture	0.06	1.000	0.37	1.000	-485.7%	0.37	1.000	-485.7%
Ancillary Energy	0.00	0.000	0.00	0.000	-	0.00	0.000	-

Note: Values in parentheses are negative values.

Table 2.10 Summer Emissions in Washington, D.C. -- High 2010 Scenario

Category	CV Scenario (summer tons)	Share	EV UCC Scenario (summer tons)	Share	Percent Reduction	EV UCT Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CC Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CT Scenario (summer tons)	Share	Percent Reduction
CO ₂ - TOTAL	266,804	1.000	156,795	1.000	41.2%	173,488	1.000	35.0%	166,081	1.000	37.8%	176,193	1.000	34.0%
CV/Power Plant Operation	209,510	0.785	106,824	0.681	49.0%	121,621	0.701	41.9%	114,866	0.692	45.2%	123,763	0.702	40.9%
Fuel Production	29,204	0.109	10,712	0.068	63.3%	12,465	0.072	57.3%	11,886	0.072	59.3%	13,019	0.074	55.4%
Vehicle Manufacture	16,867	0.063	31,137	0.199	-84.6%	31,137	0.179	-84.6%	31,137	0.187	-84.6%	31,137	0.177	-84.6%
Ancillary Energy	11,223	0.042	8,122	0.052	27.6%	8,265	0.048	26.4%	8,192	0.049	27.0%	8,275	0.047	26.3%
Share Summer is of total	0.31		0.26			0.27								
CH ₄ - TOTAL	427	1.000	422	1.000	1.3%	450	1.000	-5.2%	408	1.000	4.6%	416	1.000	2.6%
CV/Power Plant Operation	22	0.050	6	0.015	71.5%	5	0.012	74.6%	5	0.013	74.8%	5	0.012	77.1%
Fuel Production	188	0.440	313	0.742	-66.5%	341	0.758	-81.5%	300	0.735	-59.5%	308	0.741	-64.1%
Vehicle Manufacture	1	0.003	2	0.005	-58.4%	2	0.004	-58.4%	2	0.005	-58.4%	2	0.005	-58.4%
Ancillary Energy	217	0.507	101	0.239	53.5%	101	0.225	53.2%	101	0.247	53.5%	101	0.243	53.4%
Share Summer is of total	0.30		0.22			0.24								
TSP - TOTAL	45	1.000	75	1.000	-67.5%	81	1.000	-79.5%	79	1.000	-75.9%	83	1.000	-84.4%
CV/Power Plant Operation	9	0.209	30	0.393	-215.7%	35	0.431	-271.0%	33	0.420	-254.3%	37	0.445	-293.3%
Fuel Production	3	0.063	1	0.014	62.8%	1	0.015	56.5%	1	0.015	57.9%	1	0.016	53.7%
Vehicle Manufacture	30	0.672	43	0.569	-41.9%	43	0.531	-41.9%	43	0.542	-41.9%	43	0.517	-41.9%
Ancillary Energy	3	0.057	2	0.024	29.1%	2	0.023	28.0%	2	0.023	28.3%	2	0.022	27.6%
Share Summer is of total	0.28		0.30			0.30								
SO _x - TOTAL	192	1.000	2,019	1.000	-954.4%	2,115	1.000	-1004.6%	2,073	1.000	-982.6%	2,145	1.000	-1020.2%
CV/Power Plant Operation	24	0.124	441	0.219	-1755.3%	534	0.253	-2146.7%	493	0.238	-1974.0%	564	0.263	-2268.8%
Fuel Production	42	0.219	17	0.009	58.6%	20	0.010	52.1%	19	0.009	54.6%	21	0.010	50.4%
Vehicle Manufacture	97	0.504	1,541	0.763	-1496.1%	1,541	0.728	-1496.1%	1,541	0.743	-1496.1%	1,541	0.718	-1496.1%
Ancillary Energy	29	0.153	19	0.010	33.7%	20	0.009	32.4%	20	0.009	32.8%	20	0.009	32.0%
Share Summer is of total	0.29		0.31			0.31								

Table 2.10 Summer Emissions in Washington, D.C. -- High 2010 Scenario (cont'd.)

Category	CV Scenario (summer tons)	Share	EV UCC Scenario (summer tons)	Share	Percent Reduction	EV UCT Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CC Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CT Scenario (summer tons)	Share	Percent Reduction
NO_x - TOTAL	517	1.000	326	1.000	36.8%	387	1.000	25.1%	353	1.000	31.7%	392	1.000	24.2%
CV/Power Plant Operation	307	0.594	154	0.473	49.7%	204	0.528	33.4%	183	0.519	40.4%	218	0.555	29.1%
Fuel Production	107	0.208	94	0.289	12.2%	104	0.270	2.8%	92	0.261	14.2%	96	0.245	10.5%
Vehicle Manufacture	22	0.043	45	0.139	-101.4%	45	0.117	-101.4%	45	0.128	-101.4%	45	0.115	-101.4%
Ancillary Energy	80	0.155	32	0.099	59.5%	33	0.085	59.0%	33	0.092	59.3%	33	0.084	59.0%
Share Summer is of total	0.27		0.28			0.30								
VOC - TOTAL	321	1.000	29	1.000	90.8%	32	1.000	89.9%	29	1.000	91.0%	30	1.000	90.6%
CV/Power Plant Operation	295	0.920	5	0.162	98.4%	6	0.186	98.0%	5	0.178	98.3%	6	0.197	98.0%
Fuel Production	10	0.031	18	0.610	-79.3%	20	0.606	-95.7%	17	0.588	-68.7%	17	0.579	-73.4%
Vehicle Manufacture	2	0.007	3	0.104	-40.4%	3	0.094	-40.4%	3	0.106	-40.4%	3	0.102	-40.4%
Ancillary Energy	13	0.042	4	0.124	72.4%	4	0.114	72.2%	4	0.128	72.4%	4	0.123	72.4%
Share Summer is of total	0.25		0.31			0.34								
CO - TOTAL	2,613	1.000	389	1.000	85.1%	402	1.000	84.6%	393	1.000	84.9%	399	1.000	84.7%
CV/Power Plant Operation	2,309	0.884	19	0.048	99.2%	29	0.073	98.7%	23	0.059	99.0%	29	0.071	98.8%
Fuel Production	14	0.006	18	0.046	-23.9%	20	0.049	-36.1%	17	0.044	-19.9%	18	0.045	-24.3%
Vehicle Manufacture	276	0.105	348	0.894	-26.2%	348	0.866	-26.2%	348	0.884	-26.2%	348	0.871	-26.2%
Ancillary Energy	14	0.005	5	0.013	63.8%	5	0.013	63.4%	5	0.013	63.7%	5	0.013	63.6%
Share Summer is of total	0.19		0.27			0.28								
Pb - TOTAL	0.017	1.000	0.09	1.000	-403.5%	0.09	1.000	-403.5%	0.09	1.000	-403.5%	0.09	1.000	-403.5%
CV/Power Plant Operation	0.000	0.000	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-
Fuel Production	0.000	0.000	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-
Vehicle Manufacture	0.017	1.000	0.09	1.000	-403.5%	0.09	1.000	-403.5%	0.09	1.000	-403.5%	0.09	1.000	-403.5%
Ancillary Energy	0.000	0.000	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-	0.00	0.000	-
Share Summer is of total	0.33		0.24			0.24								

Table 2.11 Annual In-Basin Emissions in Washington, D.C. -- High 2010 Scenario

Category	CV Scenario (annual tons)	Share	EV UCC Scenario (annual tons)	Share	Percent Reduction	EV UCT Scenario (annual tons)	Share	Percent Reduction
TSP - TOTAL	34	0.211	13	0.054	60.6%	24	0.091	29.5%
CV/Power Plant Operation	34	1.000	13	0.169	60.6%	24	0.251	29.5%
Fuel Production	0	0.000	0	0.000		0	0.000	
Vehicle Manufacture	0	0.000	0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000	
SO_x - TOTAL	77	0.116	7	0.001	90.5%	181	0.026	-135.3%
CV/Power Plant Operation	77	1.000	7	0.009	90.5%	181	0.154	-135.3%
Fuel Production	0	0.000	0	0.000		0	0.000	
Vehicle Manufacture	0	0.000	0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000	
NO_x - TOTAL	1,235	0.640	40	0.035	96.7%	101	0.078	91.9%
CV/Power Plant Operation	1,235	1.000	40	0.069	96.7%	101	0.139	91.9%
Fuel Production	0	0.000	0	0.000		0	0.000	
Vehicle Manufacture	0	0.000	0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000	
VOC - TOTAL	1,212	0.935	6	0.059	99.5%	7	0.077	99.4%
CV/Power Plant Operation	1,212	1.000	6	0.374	99.5%	7	0.438	99.4%
Fuel Production	0	0.000	0	0.000		0	0.000	
Vehicle Manufacture	0	0.000	0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000	
CO - TOTAL	12,776	0.921	15	0.010	99.9%	27	0.019	99.8%
CV/Power Plant Operation	12,776	1.000	15	0.230	99.9%	27	0.324	99.8%
Fuel Production	0	0.000	0	0.000		0	0.000	
Vehicle Manufacture	0	0.000	0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000	

Table 2.12 Summer In-Basin Emissions in Washington, D.C. -- High 2010 Scenario

Category	CV Scenario (summer tons)	Share	EV UCC Scenario (summer tons)	Share	Percent Reduction	EV UCT Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CC Scenario (summer tons)	Share	Percent Reduction	EV OFF-P-CT Scenario (summer tons)	Share	Percent Reduction
TSP - TOTAL	9	0.209	3	0.040	68.0%	9	0.113	2.9%	6	0.081	31.4%	10	0.124	-9.3%
CV/Power Plant Operation	9	1.000	3	0.101	68.0%	9	0.262	2.9%	6	0.194	31.4%	10	0.278	-9.3%
Fuel Production	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
Vehicle Manufacture	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
SO_x - TOTAL	24	0.124	(7)	-0.004	129.9%	85	0.040	-257.5%	23	0.011	2.7%	93	0.043	-290.2%
CV/Power Plant Operation	24	1.000	(7)	-0.016	129.9%	85	0.159	-257.5%	23	0.047	2.7%	93	0.165	-290.2%
Fuel Production	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
Vehicle Manufacture	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
NO_x - TOTAL	307	0.594	8	0.024	97.4%	42	0.108	86.4%	28	0.079	90.9%	50	0.126	83.8%
CV/Power Plant Operation	307	1.000	8	0.051	97.4%	42	0.204	86.4%	28	0.152	90.9%	50	0.228	83.8%
Fuel Production	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
Vehicle Manufacture	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
VOC - TOTAL	295	0.920	1	0.039	99.6%	2	0.073	99.2%	2	0.067	99.3%	2	0.078	99.2%
CV/Power Plant Operation	295	1.000	1	0.238	99.6%	2	0.390	99.2%	2	0.376	99.3%	2	0.397	99.2%
Fuel Production	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
Vehicle Manufacture	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
CO - TOTAL	2,309	0.884	2	0.006	99.9%	10	0.026	99.5%	7	0.019	99.7%	10	0.025	99.6%
CV/Power Plant Operation	2,309	1.000	2	0.117	99.9%	10	0.356	99.5%	7	0.322	99.7%	10	0.350	99.6%
Fuel Production	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
Vehicle Manufacture	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	
Ancillary Energy	0	0.000	0	0.000		0	0.000		0	0.000		0	0.000	

Primary Energy Resource Consumption

* In this scenario, the introduction of EVs results in decreased fuel use in and emissions from all power plants serving Houston because the increased electricity demand due to EVs is projected to cause the utility company to add new, highly-efficient units and decrease use of older units that are less energy-efficient and more polluting. (See Chapter 5 for further discussion of this point.) The figure shows the decrease in fuel use as the portion below the X-axis (denoted as "0"). Increases in fuel use from other sources are offset by the decrease from older utility units, as shown by the dotted line near the top of the bar. The value shown over the bar is the net fuel use associated with EVs.

Figure 2.1 Primary Energy Resource Consumption in Houston and Washington, D. C. Scenarios

Figure 2.2 Comparison of Emissions in CV and EV (Unconstrained Combined Cycle) Scenarios for Washington, D.C.: Annual Results

CO₂ Emissions

Thousand
Tons

CV	Conventional Vehicle	UCC	Unconstrained Combined Cycle	OCC	Off-peak Combined Cycle
EV	Electric Vehicle	UCT	Unconstrained Combustion Turbine	OCT	Off-peak Combustion Turbine

Figure 2.3 CO₂ Emissions in Summer for Houston Scenarios

CH₄ Emissions

Figure 2.4 CH₄ Emissions in Summer for Houston Scenarios

TSP Emissions

Tons

* In this scenario, TSP emissions from fuel produced for power plants in Houston are lower with EVs than without EVs.

Figure 2.5 TSP Emissions in Summer for Houston Scenarios: Total and In-Basin

SO_x Emissions

* In this scenario, the introduction of EVs results in decreased fuel use in and emissions from all power plants serving Houston because the increased electricity demand due to EVs is projected to cause the utility company to add new, highly-efficient units and decrease use of older units that are less energy-efficient and more polluting. (See Chapter 5 for further discussion of this point.) The figure shows the decrease in power plant emissions as the portion below the X-axis (denoted as "0"). Increases in emissions from other sources are offset by the decrease from older utility units, as shown by the dotted line near the top of the bar. The value shown over the bar is the net emissions associated with EVs.

Figure 2.6 SO_x Emissions in Summer for Houston Scenarios: Total and In-Basin

NO_x Emissions

CV	Conventional Vehicle	UCC	Unconstrained Combined Cycle	OCC	Off-peak Combined Cycle
EV	Electric Vehicle	UCT	Unconstrained Combustion Turbine	OCT	Off-peak Combustion Turbine

* In this scenario, the introduction of EVs results in decreased fuel use in and emissions from all power plants serving Houston because the increased electricity demand due to EVs is projected to cause the utility company to add new, highly-efficient units and decrease use of older units that are less energy-efficient and more polluting. (See Chapter 5 for further discussion of this point.) The figure shows the decrease in power plant emissions as the portion below the X-axis (denoted as "0"). Increases in emissions from other sources are offset by the decrease from older utility units, as shown by the dotted line near the top of the bar. The value shown over the bar is the net emissions associated with EVs.

Figure 2.7 NO_x Emissions in Summer for Houston Scenarios: Total and In-Basin

Tons

CV	Conventional Vehicle	UCC	Unconstrained Combined Cycle	OCC	Off-peak Combined Cycle
EV	Electric Vehicle	UCT	Unconstrained Combustion Turbine	OCT	Off-peak Combustion Turbine

Figure 2.8 VOC Emissions in Summer for Houston Scenarios: Total and In-Basin

CO Emissions

* In this scenario, the introduction of EVs results in decreased fuel use in and emissions from all power plants serving Houston because the increased electricity demand due to EVs is projected to cause the utility company to add new, highly-efficient units and decrease use of older units that are less energy-efficient and more polluting. (See Chapter 5 for further discussion of this point.) The figure shows the decrease in power plant emissions as the portion below the X-axis (denoted as "0"). Increases in emissions from other sources are offset by the decrease from older utility units, as shown by the dotted line near the top of the bar. The value shown over the bar is the net emissions associated with EVs.

Figure 2.9 CO Emissions in Summer for Houston Scenarios: Total and In-Basin

CO₂ Emissions

CV	Conventional Vehicle	UCC	Unconstrained Combined Cycle	OCC	Off-peak Combined Cycle
EV	Electric Vehicle	UCT	Unconstrained Combustion Turbine	OCT	Off-peak Combustion Turbine

Figure 2.10 CO₂ Emissions in Summer for Washington, D.C. Scenarios

CH₄ Emissions

Tons

CV	Conventional Vehicle	UCC	Unconstrained Combined Cycle	OCC	Off-peak Combined Cycle
EV	Electric Vehicle	UCT	Unconstrained Combustion Turbine	OCT	Off-peak Combustion Turbine

Figure 2.11 CH₄ Emissions in Summer for Washington, D.C. Scenarios

TSP Emissions

Figure 2.12 TSP Emissions in Summer for Washington, D.C. Scenarios: Total and In-Basin

SO_x Emissions

Tons

CV	Conventional Vehicle	UCC	Unconstrained Combined Cycle	OCC	Off-peak Combined Cycle
EV	Electric Vehicle	UCT	Unconstrained Combustion Turbine	OCT	Off-peak Combustion Turbine

Figure 2.13 SO_x Emissions in Summer for Washington, D.C. Scenarios: Total and In-Basin

Figure 2.14 NO_x Emissions in Summer for Washington, D.C. Scenarios: Total and In-Basin

VOC Emissions

Figure 2.15 VOC Emissions in Summer for Washington, D.C. Scenarios: Total and In-Basin

CV	Conventional Vehicle	UCC	Unconstrained Combined Cycle	OCC	Off-peak Combined Cycle
EV	Electric Vehicle	UCT	Unconstrained Combustion Turbine	OCT	Off-peak Combustion Turbine

Figure 2.16 CO Emissions in Summer for Washington, D.C. Scenarios: Total and In-Basin

3.0 Conceptual Framework

The purpose of this study was to create, using a total energy cycle (TEC) approach, an inventory of the energy and environmental residuals associated with the use of EVs and compare it to that of CVs. The basic approach to compiling a TEC inventory is to (1) define all the processes involved in producing a specific "level of service" (in this case, a specific number of vehicle miles traveled), (2) quantify the energy and material inputs and outputs (including pollutant outputs) for each process needed to produce the specified level of service, and (3) sum quantities over the entire cycle to yield the overall energy cycle inventory. This general approach is followed in the EVTECA.

However, in this assessment, we examine a technology (electric vehicles) that has not yet matured or been fully introduced into the market, and that will be evolving over time. Further, the CV technology will also evolve due to technological improvements and a switch to RFG fuel. So, to conduct this assessment, we had to speculate about the exact configuration of the "system" in which the technologies fit, the operating conditions of the technology and the systems that will support their operation. Hence, many of the characteristics of the systems examined in this study depend on assumptions about the technologies or the other components of the cycle that support EV and CV production and operation.

Assumptions affect: (1) the characteristics of individual processes (which we call "unit process data") and (2) the mix of processes used to meet the demand for service or products (which we call "scenario data"). The term "unit process data" refers to data that describe the energy and material inputs to the process and the energy and material outputs of the process, including environmental residuals¹ (see Figure 3.1) under a specific set of operating conditions. Basically, a unit process is any activity one can "draw a box around" in a conceptual process diagram and that has inputs and outputs that can be quantified. Unit process data are independent of the specific conditions under which the process is used. One generic unit process data set was compiled for each process (e.g., coal mining, petroleum refining, gas pipeline, battery production, etc.) in the set of energy cycles evaluated in this study. The general format used to collect unit process data for this assessment is included in Appendix A.2.

"Scenario data," on the other hand, document assumptions about which unit processes are used in a specific energy cycle, and describe the relationship between multiple processes. Figure 3.2 shows several examples of scenario data: the end-use level-of-service, the fraction that each power plant contributes to the end-use energy demand, the miles traveled as part of the truck transportation process and the link from the truck transportation process to a specific type of coal mine (rather than a generic coal mine). These pieces of data vary with each scenario, whereas the data associated with each individual unit process (e.g., the fuel efficiency of the truck transportation process) remains the same in both scenarios. In the case of EVs, many different power plant units may be called on to provide electricity to charge EV batteries. In the context of this report, the proportion of power coming from each of those units would be considered "scenario data",

¹ A linear relationship between outputs and inputs is often assumed in studies such as this one. For example, for a specific type of power plant unit process, one could assume that "x" amount of sulfur dioxide emissions is produced per unit of fuel consumed and that this rate does not vary with the operating rate of the plant. However, outputs are not always linearly related to inputs. For instance, the rate of nitrogen oxide emissions per unit of fuel input depends on the temperature of combustion, which is, in turn, dependent on the operating rate of the plant. Emissions from conventional vehicles, too, are dependent on factors such as temperature, speed of the vehicle, etc. In such cases, algorithms, rather than fixed ratios, must be used to characterize unit processes. Sometimes, these algorithms are included in models that characterize unit processes based on certain conditions or assumptions. Hence, in such cases, it is difficult to separate the discussion of the unit process characterization and the scenario data.

whereas the emission characteristics of each unit would be considered the "unit process data." Similarly, scenario data for the RFG cycle would include the mix of feedstocks that are input into a RFG production facility. Therefore, the results of the study are a function not only of the data associated with individual processes within each energy cycle, but also the shares of competing processes and other scenario-specific data.

The following two sections provide a brief overview of the unit processes (Section 3.1) and scenario data (Section 3.2) included in the assessment.

3.1 Unit Processes

Figures 3.3 and 3.4 show the processes included in the EV and CV energy cycles, respectively. The processes are grouped into "segments" which have been numbered (e.g., S1, for segment number one; S2, for segment two, etc.). Within each of these segments, descriptions of the major processes covered in the study are listed in Table 3.1. Some segments are included in both cycles. For example, S5: Oil Refining, is included in both the EV and the RFG energy cycle, because oil is refined for use as a fuel for the electricity generation needed to power the electric vehicles and also to make the gasoline used as the fuel for conventional vehicles. Most of the data collected focuses on the operational phase of each energy cycle stage (see Figure 1.1).² Also, most of the emissions data are for air pollutants. Water pollution and solid waste data were not collected for most processes.

The data for the processes within each segment include a quantification of the inputs and outputs of each process. Other qualitative data were also gathered (see Appendix A.2 for a complete description of the information that was sought for each unit process). The derivation of the specific data is described in the chapters that follow this one. Chapter 4 describes the electric vehicle charging and end use (Segment S16) and the conventional vehicle refueling and end use (S17). The chapter explains the derivation of the inputs to the processes, which in the case of vehicles are primarily energy inputs, and the derivation of the outputs, which are confined to air pollutant emissions for CVs. The electricity generation and transmission segment (S11) is described in Chapter 5. Chapter 6 describes the fuel formulation and RFG transportation processes (S6 and S10) and all segments that precede (or are "upstream from") them (including oxygenate production and crude oil extraction, transportation and refining -- S4, S5, S6). Chapter 6 also describes fuel oil transportation (S8). Chapter 7 describes all segments upstream from the electricity generation process (S1-5, and S9), except the oil-related processes (which are discussed in Chapter 6). Chapter 8 describes the vehicle and battery manufacturing process and the production of material inputs to those processes (S14, S12, S13, and S15).

²A basic assumption is that no new coal mines, oil wells, or transmission lines would be built solely because of EV penetration. This simplifying assumption was necessary to accommodate the constraints imposed on the study. But even if new capacity of mines, wells, etc., were needed, the construction of this capacity is not expected to contribute significantly to total environmental effects, compared to the operational phase of the energy cycle. For power plants and vehicle/battery manufacturing, some of the pre- and post-operational phases, such as construction of new power plants and disposal of batteries and vehicles were studied, but were not included in the quantitative analysis.

3.2 Scenario Data

To reflect the wide variation possible in the environmental tradeoffs between EVs and CVs, the study employs several sets of scenarios that represent possible future conditions, and hence affect the scenario data associated with the EV and CV cycles. The assessment focused on four diverse locations (the metropolitan areas surrounding and including Los Angeles, Chicago, Washington, D.C. and Houston, Texas), which have different power plant mixes and climates (which affects vehicle energy use). In each location, the analysis used two different EV market-penetration assumptions (low and high). The high- and low-penetration scenarios contain different assumptions regarding the percentages of new vehicle sales that will be EVs. These assumptions affect the total number of EVs on the road in each location, the mix of types of EVs, the electricity demanded for EV charging, and the shares of electricity supplied by various power plant units, etc. The two general EV market-penetration scenario cases are described as follows:

- **Low EV Market Penetration Scenario.** This set of scenarios was based on the national EV sales projections of the Annual Energy Outlook 1993 (AEO 93) under its "mid-level oil price" projections. The AEO 93 EV sales projections assume that the California Low Emission Vehicle Program (LEVP)³ will also be adopted by New York and Massachusetts. The California LEVP mandates that 2% of passenger vehicles and light-duty trucks (3500 lb gross vehicle weight or less) sold in 1998 be zero emission vehicles (ZEV), and that this percentage will increase over time. The sales projections also assume that the provisions affecting alternative fuel vehicles in general and EVs in particular in the Energy Policy Act of 1992 and the Clean Air Act Amendments of 1990 are in place. Under these assumptions, the AEO93 projects 107,000 EV sales in the United States in 2000 and 571,916 EV sales in 2010. The total stock of EVs in 2010 is projected to be 4,621,000. Of the four regions included in the study (Los Angeles, Chicago, Houston, Washington, DC), only Los Angeles will be under the California LEVP, and the low case for Los Angeles will be identical to the ZEV requirement under the LEVP. For the other three regions, we assume a lower and slower market penetration than that required under the LEVP and assumed the same penetration rates to facilitate comparative analysis among the three regions (see Table 3.2).
- **High EV Market Penetration Scenarios.** This set of scenarios is based on the assumption that all states (beyond CA, MA, and NY) containing areas classified by the EPA as serious ozone non-attainment areas will adopt the California LEVP before 1998 when the 2% ZEV mandate applies. These states are Illinois, Indiana, Texas, Wisconsin, Maryland, Pennsylvania, New Jersey, Delaware, Georgia, Louisiana, New Hampshire, Connecticut, Michigan, Rhode Island, Virginia, and the District of Columbia. The EV penetration in three of the four study regions (Chicago, Houston, and Washington) is assumed to be consistent with the California LEVP. For Los Angeles, we assume that the penetration of EVs will be that percentage proposed in the 1994 Air Quality Management Plan by the South Coast Air Quality Management District (see Table 3.3).

Utility-related scenario data include data or assumptions about when EVs will be charged and what type of power plants will be built if incremental power plant capacity is required. For example, some scenarios assume EVs begin recharging as soon as they return "home" at the end of the day (unconstrained charging); other scenarios assume EVs are only charged "off-peak" because of some unspecified utility

³ Some changes were recently made to the ZEV requirements in California, but they should not strongly affect the EV penetration rate in 2010 or the results of this analysis.

policies. Each of these two assumptions results in different power plant mixes to provide the electricity for EV recharging.

Both sets of charging assumptions result in incremental power plant capacity requirements, though the unconstrained charging has greater requirements. We assume two alternative types of power plants (combustion turbine and combined cycle) can be added, each with different costs, efficiencies and emissions. Again, the choice of power plants to be added affects the mix of fuels used to provide the electricity for EV recharging.

These scenarios illustrate that many factors will affect the configuration and operating conditions of the system that supports EV production and use. We attempted to examine variation in these factors through use of a number of discrete scenarios. Aside from the ones that we varied in these major scenarios, many other factors affect the configurations of the EV and CV energy cycles, and hence the environmental characterization of those energy cycles. For example, the method of transportation of RFG from the refinery to the RFG distribution center can affect the overall environmental profile of the CV energy cycle because barge transport has different emissions per mile than a rail or truck transport mode. Generally, assumptions for factors like these were made and then remained static in all scenarios. A more detailed description of the scenario data and assumptions made in order to conduct this assessment can be found in the discussions within the next five chapters of this report.

Figure 3.1 How Unit Process Data Fits into Scenarios

Scenario #1

Scenario #2

Figure 3.2 Example Scenarios

Figure 3.3 Conventional Vehicle Energy Cycle

Figure 3.4 Electric Vehicle Energy Cycle

Table 3.1. EVTECA Segments and Processes Included

Segment	Processes Included
S1: Coal mining and transportation	<ol style="list-style-type: none"> 1) surface coal mining (west) with on-site coal preparation 2) surface mining (east) with on-site preparation 3) underground mining (east) with on-site coal preparation 4) coal transport to power plant by truck 5) coal transport to power plant by train
S2: Natural gas extraction, processing and transportation	<ol style="list-style-type: none"> 1) natural gas extraction from onshore and offshore gas wells 2) the processing of raw natural gas 3) the transmission of natural gas through a pipeline
S3: Uranium mining, extraction, processing, fuel fabrication and transportation	<ol style="list-style-type: none"> 1) open-pit (surface) uranium mining 2) underground uranium mining 3) uranium milling 4) uranium conversion to UF₆ 5) UF₆ enrichment (gaseous diffusion) 6) fuel fabrication 7) transport by truck (between various stages)
S4: Crude oil extraction and transportation	<ol style="list-style-type: none"> 1) oil field production (and processing of crude in the field) 2) transportation by heavy-duty diesel-fueled truck 3) transportation by rail (oil train) 4) transportation by domestic barges 5) transportation by oil tanker 6) crude oil pipeline
S5: Crude Oil Refining	<ol style="list-style-type: none"> 1) refining of crude oil to gasoline and fuel oil, and other products

Segment	Processes Included
S6: Fuel Formulation	1) blending of the components of reformulated gasoline*
S7: Oxygenate Feedstock Production, Processing and Transportation	1) butane production 2) methanol production 3) MTBE production 4) feedstock production** 5) feedstock transportation** 6) ethanol production**
S8: Fuel oil transportation, distribution and storage	No processes included.
S9: Hydropower and other Renewables	1) production of power from hydroelectric power plants and renewables (These processes have no emissions.)
S10: Reformulated Gasoline Transportation	1) transportation of RFG by truck from refinery to distribution centers 2) transportation of RFG by pipeline from refinery to distribution centers
S11: Electricity Generation and Transmission	1) generation of electricity via various non-renewable technologies
S12: Electric vehicle manufacturing	1) vehicle assembly (no emissions)

* This process has no environmental residuals in this analysis.

** These processes are relevant to the Chicago scenario. Chicago was not fully analyzed due to resource constraints.

Segment	Processes Included
S13: Battery manufacturing	1) battery module manufacturing (no emissions)
S14: Extraction and Processing Involved in Manufacture of Industrial Commodities used in Vehicles and Batteries	1) steel making including: coking, sintering, pigiron production via blast furnace, steel production via basic oxygen process and electric arc furnace, steel sheet production, steel parts stamping 2) iron casting 3) aluminum production including: bauxite extraction, alumina production, ingot production via Hall-Heroult Process, virgin aluminum casting, aluminum milling, aluminum parts stamping, recycled aluminum casting, recycled aluminum ingot production 4) copper production 5) plastic production including polypropylene polymerization, PET production, and miscellaneous plastic production 6) rubber production 7) glass production including float glass and fiber glass 8) lead production including primary and secondary processes 9) sulfuric acid production 10) beta aluminum electrolyte (ceramic) production 11) cadmium production 12) nickel production
S15: Conventional vehicle manufacturing and reclamation	1) vehicle assembly (no emissions)
S16: Electric Vehicle Charging and End-use	1) electric vehicle charging (no emissions) 2) electric vehicle end-use (no emissions)
S17: Conventional Vehicle Fueling and End-Use	1) conventional vehicle fueling and operation

**Table 3.2. Percent Sales of New Passenger Vehicles and Light-duty Trucks --
Low Penetration Case**

Year	Los Angeles	Chicago	Houston	Washington, DC
1998	2	0	0	0
1999	2	0	0	0
2000	5	0	0	0
2001	5	1	1	1
2002	5	1	1	1
2003	10	2	2	2
2004	10	2	2	2
2005	10	2	2	2
2006	10	3	3	3
2007	10	3	3	3
2008	10	3	3	3
2009	10	3	3	3
2010	10	3	3	3

**Table 3.3. Percent Sales of New Passenger Vehicles and Light-duty Trucks --
High Penetration Case**

Year	Los Angeles	Chicago	Houston	Washington DC
1998	2	2	2	2
1999	2	2	2	2
2000	5	5	5	5
2001	5	5	5	5
2002	5	5	5	5
2003	10	10	10	10
2004	10	10	10	10
2005	20	10	10	10
2006	20	10	10	10
2007	35	10	10	10
2008	35	10	10	10
2009	50	10	10	10
2010	50	10	10	10

4.0 Vehicle Analysis

This chapter describes the methods and data employed in the vehicle operation segments of the EVTECA. For the electric vehicle (EV) operation segment, the principal calculations involve estimating the total amount of electricity needed to operate EVs of various types traveling a given number of vehicle miles/day. The electric vehicle operation itself is assumed to have no direct environmental residuals (i.e., it emits no air pollutants or water pollutants; no solid waste is produced; no natural resources are consumed, etc.). The analysis, therefore, focused on characterizing the stock of vehicles under each scenario, their daily travel and the amount of electricity needed to operate the vehicles. A summary of the major methodological steps to this process is found in Section 4.1. Figures 4.1 and 4.2 show the segments of the CV and EV energy cycles described in this chapter.

For the conventional vehicle (CV) operation segment, the same vehicle stock characteristics and total vehicle miles were assumed as in the electric vehicle segment. However, these vehicles are fueled with reformulated gasoline (RFG) instead of being powered with batteries that are recharged via electric current. In addition, operation of these CVs does generate pollutants (emissions to air). An overview of the calculation of fuel consumption and air pollutant emissions from the CVs is described in Section 4.2.

Appendices B.1 through B.6 provide additional detail on key topics referenced in Sections 4.1 and 4.2.

4.1 Electric Vehicles

The total daily electricity demand generated by the EVs in the scenarios is a function of a number of variables. These include:

- the total number of EVs in operation (by type of vehicle, battery, and use);
- the energy efficiency of each EV;
- the daily recharging requirements of each EV.

This section reviews these variables and how total EV electricity demand is estimated for each scenario. This section also describes how these daily estimates are disaggregated into hourly estimates of energy demand and then demand by five-minute intervals. Finally, this section presents the seasonal EV electricity demand estimates used in the EVTECA.

4.1.1 EV Stock

General assumptions regarding EV market penetration are described in Chapter 3.0. In effect, the EV market penetration scenarios are based on the assumption that, beginning in 1998, EVs will account for a specific percentage of new light-duty vehicle (LDV) sales in each of the four metropolitan regions.

In order to translate these percentages into estimates of the number of EVs in operation (the EV stock) in 2000 and 2010, projections of total annual LDV sales in the four regions were developed. These projections are described in Appendix B.1. Sales are disaggregated into cars, vans and light trucks in household and fleet applications.

Figure 4.1 Segments within the Conventional Vehicle Energy Cycle Discussed in Chapter 4 (shown with dotted lines)

Figure 4.2 Segments within the Electric Vehicle Energy Cycle Discussed in Chapter 4 (shown with dotted lines)

We included light trucks as well as cars and vans in these projections because the Zero Emission Vehicle (ZEV) sales requirements of the California Air Resources Board (CARB) apply to all LDVs, which include light trucks. When assessing likely market niches for EVs, we found no electric light truck models or prototypes being developed by OEMs. Given this fact and the fact that the total ZEV sales requirement can be met with the production of electric cars and vans only, we do not include electric light trucks in our analysis.

EV energy use varies by vehicle type (car or van) and vehicle use (household and fleet application). This analysis assumes that initially EVs will be sold predominantly (though not exclusively) to the fleet van market. Gradually the fleet van market will be exhausted and sales into the car market will increase. We assume no electric vans will be sold for household use and, in the car market, EVs will be sold predominantly to the fleet market. Only in the LA High scenario will household car applications overtake fleet car applications. Table 4.1 illustrates these assumptions. Appendix B.1. contains the assumptions for all the years in this analysis.

The estimates of electric fleet van, fleet car, and household car sales are further disaggregated by size of van and car (e.g., minivan and full size van). Again this is necessary because the energy efficiency of EVs varies by vehicle size. Appendix B.2 contains an evaluation (Table B.2.5) of existing OEM EV models and prototypes. Based on that evaluation, a list of the sizes of vehicles that would be used in both fleet and household applications was developed. (It was this evaluation which concluded that there would be no vans used in household applications.) Appendix B.1 contains the specific disaggregation of cars and vans by size used in this analysis (Tables B.1.12 and B.1.13) and the assumptions used to make this disaggregation.

The estimates of electric fleet van, fleet car, and household car sales, by size, were further disaggregated by battery type. Again, this was necessary because the energy efficiency of EVs varies by battery type. Batteries were selected for each EV type after reviewing information on advances in battery technologies and manufacturer intentions to use certain battery types. The analysis concluded that through the vehicle model year (MY) 2002, Lead-Acid (Pb-Acid) batteries will be used in mini-compact cars, compact cars, and full-sized vans, Sodium-Sulfur (Na-S) batteries in mini-mini vans, and Nickel-Cadmium (Ni-Cd) batteries in minivans. Beginning with MY 2003 vehicles, this analysis assumes advanced Pb-acid batteries will be used in minicompact cars only and the Na-S, Ni-Cd and Nickel-Metal Hydride (Ni-MH) batteries will be used in compact cars, minivans and full size vans. Where more than one battery type is used in a specific vehicle type, this analysis assumes that the total number of EVs for that EV type is divided evenly among the battery types.

The text above has discussed how the EV sales estimates by year, vehicle type, use, size, and battery type were developed. These estimates were then input to a model which estimates vehicle survival and usage rates. Estimates of vehicle stock were developed for the years 2000 and 2010 in all four regions under both scenarios. Appendix B.1 contains the estimates of stock by vehicle type, application, vehicle size, and battery. Table 4.2 presents selected results; specifically it presents the stock in 2010 in the four regions, assuming implementation of the CA ZEV mandate. Depending on the region, 150,000 to 400,000 EVs would be in operation in 2010. Twenty percent (20%) of the vehicles would be fleet vans, 50% fleet cars, and 30% household cars. Thirty percent (30%) would use Na-S batteries, 28% Ni-Cd, 28% Ni-MH, and 14% Pb-Acid. These percentages are different in the other scenarios and in 2000.

4.1.2 EV Energy Efficiency

The energy efficiencies of the EVs (i.e., the kWh needed per mile of vehicle travel) included in this analysis were estimated using the EAGLES software package. EAGLES is an upgraded and expanded version of an earlier model, DIANE, which is an interactive computer model used to simulate battery performance in EV applications. The analysis of energy efficiencies is composed of two parts. For each combination of battery type and EV type discussed above, the size of the battery is determined on the basis of meeting specific minimum performance characteristics (range, top speed, acceleration) at the end of the useful life and at the lowest allowable charge of the battery. Once the size of the battery and its capacity have been determined, actual performance of the vehicle under a given driving cycle is evaluated.

Battery Size

Assumptions regarding battery performance characteristics are provided in Appendix B.2, Table B.2.3. These assumptions are based on the tested performance of existing batteries and account for progress in EV battery technologies over time. By the latter part of the study period, the Ni-MH and Na-S batteries are projected to meet the USABC mid-term goals for both specific energy and power.

In EAGLES, these battery performance characteristics are combined with:

- vehicle mission characteristics (design range, payload, top speed and acceleration time, assumptions for which are found in Appendix B.2 and which change over time);
- vehicle characteristics (curb weight less battery weight, drag coefficient, rolling resistance, frontal area, drivetrain and motor/controller efficiencies, percent of braking converted to useful energy, assumptions for which are found in Appendix B.3 and which change over time); and
- driving patterns (see below).

A second-by-second power demand is completed and battery weight for the vehicles determined from the assumed specific power and energy attributes of the battery.

Driving Cycle and Base Case Energy Efficiency

Vehicle energy consumption varies significantly with trip characteristics (i.e., average speed, top speed, maximum acceleration rate, and idling time). In this analysis, driving cycles were designed to represent driving patterns in a particular environment. Two driving cycles were selected: the Federal Urban Driving Schedule (FUDS), which is used for all electric vans; and the LA-92, which is used for all electric cars. (USEPA and CARB have developed these driving cycles for vehicle emission testing.) Both cycles are representative of urban driving, but the LA-92 cycle incorporates more aggressive driving patterns. FUDS has a lower average speed, lower top speed, and longer idling time than LA-92. The rationale for selection of these two driving cycles is discussed in Appendix B.4, as are the specifications of the two cycles.

Using these driving cycles, the base case energy efficiencies (without consideration of heating and cooling requirements) of the various EVs are estimated by EAGLES. These energy efficiencies are presented in Appendix B.3 (Table B.3.8). By the latter model years (MY 2008-2010), the base case energy efficiencies of the electric cars range from 0.21 kWh/mile to 0.25 kWh/mile depending on battery type, those

of minivans from 0.23 kWh/mile to 0.26 kWh/mile, and that of full size vans from 0.38 kWh/mile to 0.43 kWh/mile.

Effect of Heating and Cooling Requirements on Energy Efficiency

Energy is consumed in heating and cooling the interior cabs of EVs for passenger comfort. Appendix B.3 contains a description of the air conditioning and heating/defrosting systems assumed in this analysis. Vehicle waste heat and certain design measures assist in meeting heating and cooling requirements, but the battery is the major source of energy for this purpose.

A thermal load model was used to produce EV heating and cooling loads. Energy consumption due to heating and cooling loads is calculated using the average summer high and winter low temperatures for the four metropolitan areas. Appendix B.3 contains estimates of these temperatures (Table B.3.4) as well as the additional energy requirement per mile due to heating and cooling loads (Table B.3.8). Heating and cooling loads can add as little as 0.008 kWh/mile and as much as 0.124 kWh/mile to the base energy requirements of MY 2008-2010 EVs, depending on vehicle/battery type and region. In Chicago, with the greatest heating requirements in the winter, approximately 15% more energy (than the base) will be used for heating cars and 30% more for heating vans. In Houston, with the greatest cooling requirements in the summer, 15-20% more energy will be required to air condition cars and approximately 25% more for vans.

Adjustments for Thermal Loss and Final Energy Efficiency Estimates

The energy efficiencies presented in Table B.3.8 do not include the effects of thermal loss on Na-S batteries. (Thermal loss is a factor uniquely affecting Na-S batteries.) A thermal management system is needed to maintain Na-S operating temperatures. This system increases vehicle energy consumption. The energy efficiency estimates used in this analysis are adjusted to account for this increased energy consumption (see Appendix B.3). The final energy efficiency estimates for all the vehicle and battery types are shown in Table 4.3.

4.1.3 Daily Recharge Requirements

The daily recharge requirements of the average EV is dependent upon the energy efficiency of the EV in kWh/mile (discussed above in Sec 4.1.2), the daily travel (in number of miles) of the EV, and the frequency of recharge. Appendix B.4 describes the development of estimates of the average daily travel by vehicle type in the four regions. Table 4.4 presents the estimates.

The household daily mileage estimates are derived from 1990 National Personal Transportation Study (NPTS) for each region. NPTS collected data on household trips per day and average trip lengths. It is assumed that EVs will be used in multi-vehicle households and used to make short distance trips. Trip lengths for trips that were less than or equal to 30 miles each were used in determining the average trip length of household vehicles for which EVs could be substituted. Daily mileage results from multiple trips per day.

The fleet daily mileage estimates are derived from a survey of commercial fleet vehicles. The majority of fleet cars and trucks in the four metropolitan areas travel less than 90 miles per day. EVs designed with 90-mile driving range will be able to replace a majority of fleet vehicles. Trip lengths for trips

that were less than 90 miles were used in determining the average trip length of the fleet vehicles for which EVs could be substituted.

Finally, seasonal variation in daily VMT exists. The estimates used in this analysis are applied to all regions and vehicle types. Appendix B.5 contains the seasonal-adjustment factors applied to the daily VMT: 1 for the whole year, 1.019 for spring, 1.084 for summer, 0.992 for fall, and 0.905 for winter. The source of these factors is explained in Appendix B.

These daily mileage estimates (varied by season) combined with EV stock and the seasonal energy efficiencies of EVs result in total daily electricity use estimates for each region and each scenario. We assume that EVs are recharged every day, so that the estimates for total daily use are also the estimates for total daily electricity demand. We draw no distinction between weekday and weekend travel for household vehicles. Fleet vehicles are assumed not to operate on weekends. Thus, two average daily demand estimates are derived for each region, scenario, and season: one for the average weekday and one for the average weekend day.

4.1.4 End-of-Use Recharge Requirements by Hour and Five-Minute Interval

In Section 4.1.3, the derivation of the total daily electricity demand associated with EVs is presented. For purposes of conducting the utility analysis, this daily demand was disaggregated into hourly demand estimates and then into demand for 5-minute intervals. Hourly demand estimates are based on 1) battery recharging profiles, 2) battery depth of discharge, and 3) starting time of the battery recharge. Appendix B.5 presents the derivation of these three items. A brief explanation is provided below.

Battery recharge profiles

Battery recharge profiles are profiles of the hourly electricity input required to recharge batteries. For batteries that are completely discharged, power requirements are generally greatest at the beginning of the charge. Power required over time varies by battery type. Battery manufacturers recommend specific recharge methods (e.g., combinations of constant current and/or constant voltage for specific time periods) for specific battery types. The recommended recharge methods determine the shape of the recharge profiles. Appendix B.5 summarizes the recharge methods recommended and presents the final profiles used in this analysis. Assumptions about the duration of each step, change in voltage, and change in current are made for the recharging of batteries with 100% depth of discharge (DOD).

Recharging a battery with less than 100% DOD means the battery would enter the recharge profile at an intermediate point. Thus the early part (high power) of the recharge profile may be skipped. To precisely determine the point at which recharge occurs, the DOD of batteries needs to be calculated. Therefore, to compute hourly energy demand profiles, a profile of the DOD of the entire battery stock must be estimated.

Battery DOD at the Beginning of EV Recharge

We assume that batteries will be recharged every day after the vehicles' last trip (end-of-use charging). The battery DOD was determined by EV daily mileage, EV energy efficiency/mile, and EV battery capacity. The average daily mileage was presented in Table 4.4. However, using the average daily mileage for all household vehicles is not desirable for DOD calculations. (All the vehicles of a particular

battery type would have the same DOD.) Therefore, we used NPTS data to develop a distribution of daily travel around the average, but ranging from 0-100 miles (or 80 miles for pre-MY 2003 EVs).

The energy efficiencies of the EVs was presented in Section 4.1.2. For purposes of calculating battery DOD, EV electricity consumption is calculated from the batteries rather than from wall outlets. This calculation is an intermediate step in vehicle energy efficiency calculations already presented.

Battery energy capacity (kWh) is calculated from the battery weight for a particular EV type and the specific energy of the battery type used in the EV. Battery weight for each EV is presented in Appendix B.3 and specific energy for each battery type in Appendix B.2. A third variable affects Pb-acid battery capacity: ambient temperature. In this analysis, the average seasonal temperatures of each of the four regions were used to adjust Pb-acid battery capacity (see Appendix B.5). The final battery capacities are presented in Table 4.5.

Starting Time of EV Recharge

While utilities may use a variety of policies to control EV charging time, in our base cases we assume that no such policies exist and EV users will recharge as soon as they return home after their last trip. The 1990 NPTS contains data on the distribution of the time when the last trip by a household vehicle ends. The majority of the trips end between 3 p.m. and midnight. The distribution varies by region. Appendix B.5 contains the distribution for each region. No such data exists for fleet vehicles. For fleet vehicles, it was assumed that 50% of the vehicles would begin recharge between 4 and 5 p.m. and 50% between 5 and 6 p.m.

Summary of Hourly Recharge Requirements

The DOD and starting time estimates are combined to provide a distribution of EV battery DOD when EVs start to be recharged each day. The starting times are estimated by hour. The results are presented in Appendix B.5. The distribution was combined with the recharging profiles for each battery type and battery size to develop estimates of hourly electricity demand to recharge EVs for the scenarios. Charger efficiency is also taken into account. The hourly demand estimates, when summed for each season and year are consistent with those presented in Appendix B.4.

The hourly demand estimates were further disaggregated into five-minute intervals. For each hourly demand estimate, a uniform distribution of vehicle arrivals and recharge starting times over five-minute intervals was assumed. This level of disaggregation was used in the utility analysis (see Section 5).

4.1.5 Seasonal EV Electricity Demand Estimates

Total EV/CV VMT for each season, year and region is presented in Table 4.6. The table also shows electricity consumption in EVs, both including and excluding a 5% assumed transmission-and-distribution loss. The EV electricity consumption is based on the daily recharge estimates discussed in Section 4.1.3.

4.2 Conventional Vehicles

The emissions and fuel economy of the conventional gasoline vehicles replaced by EVs are calculated for the years 2000 and 2010. It is assumed that EVs replace CVs on a one-for-one basis in each

vehicle model year (MY) included in this analysis. Thus, the CVs included here range from MY 1998 to MY 2010 vehicles.

Emissions are estimated for each of several air pollutants -- VOC, CO, NO_x, SO_x, CO₂, PM, and CH₄. VOC emissions include exhaust, diurnal, hot soak, refueling, running loss, and resting loss emissions. The method used to estimate these emissions is described in Appendix B.6. A summary is provided below. Appendix B.6 contains the estimated emissions of CVs on a per mile basis for each vehicle type, region, season, and year of analysis.

Mobile5a was developed by EPA to estimate vehicle emissions rates in all states except California. EMFAC7 was developed by CARB to estimate vehicle emissions in that state. However, since Mobile5a can generate the model-year-specific emission (VOC, CO, NO_x) rates which are needed for the EVTECA and EMFAC7 cannot, Mobile5a was used for both non-California and California cities.

In designing the Mobile5a input program for each city, the mobile source control measures already adopted in the 1990 Clean Air Act Amendments and adopted by CARB are considered. In particular, Federal Tier 1 standards, California's low-emission vehicle (LEV) standards, Federal and California RFG requirements, Stage II gasoline vapor recovery system, on-board vehicle refueling control systems, and enhanced inspection/maintenance programs are included.

As stated before, two driving cycles -- the LA-92 cycle and FUDS cycles -- were selected for use in the EVTECA. Mobile5a uses speed correction factors to simulate emissions for different driving cycles. The LA-92 cycle was developed very recently, and LA-92 emission test results have not been used in developing Mobile5a. Speed correction factors currently incorporated in Mobile5a, therefore, may not represent the emission characteristics of the LA-92 driving cycle. For example, emission simulations with Mobile5a show decreased emissions when changing from the FUDS to the LA-92 cycle. However, actual test results show significant increases in emissions when changing from the FUDS to the LA-92 cycle. Because of concern that Mobile5a may misrepresent the LA-92 cycle, vehicle emissions under the LA-92 cycle are estimated outside of Mobile5a. First FUDS emissions are estimated with Mobile5a. Then the FUDS emissions are adjusted using known emission differences between the FUDS and LA-92 cycles.

Vehicle CO₂ emissions are estimated with a carbon balance approach which assumes that all carbon contained in RFG converts to CO₂ and CO emissions. A small amount of carbon is contained in VOC and CH₄ emissions; this amount is ignored. Grams-per-mile carbon consumption is calculated from vehicle fuel economy, RFG density and carbon ratio of RFG.

Vehicle SO_x emission are estimated by assuming that all the sulfur contained in RFG is converted into SO₂. Exhaust PM emissions are obtained from EPA's AP-42 document. Tirewear and brakewear PM emissions are assumed to be the same between EVs and CVs. Finally CH₄ emissions are estimated to be approximately 7% of the VOC emissions of each CV.

Fuel economy estimates for CVs are developed using the EAGLES model developed at Argonne National Laboratory. EAGLES estimates CV fuel economy by considering the amount of energy required to overcome vehicle drag force, rolling resistance force, and kinetic force. To run EAGLES, input parameters regarding vehicle weight, engine size, drag coefficient, rolling resistance, and powertrain efficiency are required. Improvements in these parameters between MY 1998 CVs and MY 2010 CVs are assumed in EAGLES simulations. Fuel economy is estimated under the FUDS cycle for fleet vehicles and under the LA-

92 cycle for household vehicles. The fuel economy penalty of CV air conditioning systems is included in EAGLES simulations. Appendix B.3 contains the fuel economy estimates of the CVs. By MY 2008-MY 2010 the base fuel economy of the CVs replaced by EVs is 36.4 mpg for minicompacts, 29.1 mpg for compacts, 23.2 mpg for minivans, and 14.8 for full-size vans.

Total gasoline consumption of the CVs being replaced by the EVs in each region, scenario and year is based on the stock of CVs being replaced, their fuel economy and their VMT. Table 4.6 presents the total gasoline consumption by the CVs being replaced by EVs in each scenario. Emissions from CVs, by scenario, year, and season are presented in Table 4.7.

Table 4.1 Fleet and Household EV Sales
Percentage of Total EV Sales (by Scenario & for Selected Years)

Years	1998	2000	2005	2010
LOW PENETRATION SCENARIOS				
Houston, Washington, Chicago				
Fleet Vans	NA	NA	80	60
Fleet Cars	NA	NA	15 ^a	30 ^b
Household Cars	NA	NA	5 ^a	10 ^b
TOTAL	NA	NA	100	100
Los Angeles				
Fleet Vans	60	60	20	20
Fleet Cars	27	27	53	53
Household Cars	13	13	27	27
TOTAL	100	100	100	100
HIGH PENETRATION SCENARIOS				
Houston, Washington, Chicago				
Fleet Vans	60	60	20	20
Fleet Cars	27	27	53	53
Household Cars	13	13	27	27
TOTAL	100	100	100	100
Los Angeles				
Fleet Vans	60	60	17	7
Fleet Cars	27	27	41	38
Household Cars	13	13	42	55
TOTAL	100	100	100	100

NA = Not applicable; no EV Sales in this year

^aFor Houston and DC; Chicago is 10% Fleet Cars and 10% Household Cars

^bFor Houston and DC; Chicago is 21% Fleet Cars and 19% Household Cars

**Table 4.2 EV Stock in 2010 in the Scenario that Assumes
All Regions Meet the CA ZEV Mandate ^a**

Vehicle & Battery Type	Number of Vehicles on the road in 2010 in each Metropolitan Area			
	Chicago	Houston	Washington DC	Los Angeles
Fleet Vans				
Pb-Acid	2,978	2,192	1,603	4,642
Na-S	22,733	16,784	12,231	35,430
Ni-Cd	15,786	11,670	8,492	24,599
Ni-MH	15,786	11,670	8,492	24,599
TOTAL	57,283	42,316	30,818	89,270
Fleet Cars				
Pb-Acid	8,228	6,059	4,428	12,827
Na-S	42,154	31,165	22,677	65,692
Ni-Cd	42,154	31,165	22,677	65,692
Ni-MH	42,154	31,165	22,677	65,692
TOTAL	134,690	99,554	72,459	209,903
Household Cars				
Pb-Acid	26,395	19,493	14,203	41,135
Na-S	15,441	11,415	8,307	24,064
Ni-Cd	15,441	11,415	8,307	24,064
Ni-MH	15,441	11,415	8,307	24,064
TOTAL	72,718	53,738	39,124	113,327
GRAND TOTAL	264,691	195,608	142,401	412,500

^a The California ZEV Mandate is assumed to be met in the high-penetration scenarios in Chicago, Houston, and Washington, DC and in the low-penetration scenarios in Los Angeles.

Table 4.3 EV Electricity Consumption in kWh/Mile from Wall Outlets: Including Heating, Cooling, and Thermal Loss

PRE-2003 YEARS:		Chicago				Houston				Los Angeles				Washington, DC			
Appliance	Vehicle Battery	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Hhold	2-seater, Pb-Acid	0.245	0.264	0.245	0.263	0.245	0.267	0.245	0.252	0.245	0.264	0.245	0.251	0.245	0.266	0.245	0.257
	Compact, Pb-Acid	0.279	0.319	0.279	0.316	0.279	0.324	0.279	0.295	0.279	0.319	0.279	0.291	0.279	0.321	0.279	0.304
Fleet	Compact, Pb-Acid	0.279	0.319	0.279	0.316	0.279	0.324	0.279	0.295	0.279	0.319	0.279	0.291	0.279	0.321	0.279	0.304
	M Mvan, Na-S	0.279	0.300	0.274	0.387	0.254	0.295	0.251	0.275	0.260	0.295	0.257	0.275	0.252	0.292	0.255	0.304
	Minivan, Ni-Cd	0.297	0.354	0.297	0.387	0.297	0.367	0.297	0.323	0.297	0.357	0.297	0.317	0.297	0.360	0.297	0.343
	F-S Van, Pb-Acid	0.510	0.601	0.510	0.648	0.510	0.643	0.510	0.551	0.510	0.604	0.510	0.542	0.510	0.610	0.510	0.579

Note: Total electricity consumption includes cooling (summer), heating (winter) and thermal loss (Na-S)

YEARS 2003-2007:		Chicago				Houston				Los Angeles				Washington, DC			
Appliance	Vehicle Battery	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Hhold	Mi-Com, Pb-acid	0.250	0.278	0.250	0.276	0.250	0.283	0.250	0.261	0.250	0.279	0.250	0.260	0.250	0.281	0.250	0.268
	Compact, Na-S	0.388	0.377	0.375	0.553	0.347	0.362	0.335	0.376	0.346	0.367	0.337	0.364	0.345	0.355	0.339	0.417
	Compact, Ni=Cd	0.299	0.336	0.299	0.333	0.299	0.341	0.299	0.314	0.299	0.336	0.299	0.311	0.299	0.338	0.299	0.322
Fleet	Compact, Ni-MH	0.288	0.328	0.288	0.325	0.288	0.333	0.288	0.304	0.288	0.328	0.288	0.298	0.288	0.330	0.288	0.313
	Compact, Na-S	0.307	0.322	0.301	0.398	0.296	0.323	0.290	0.318	0.290	0.319	0.286	0.304	0.316	0.334	0.312	0.374
	Compact, Ni-Cd	0.299	0.336	0.299	0.333	0.299	0.341	0.299	0.314	0.299	0.336	0.299	0.311	0.299	0.338	0.299	0.322
	Compact, Ni=MH	0.288	0.328	0.288	0.325	0.288	0.333	0.288	0.304	0.288	0.328	0.288	0.306	0.288	0.330	0.288	0.313
	Minivan, Na-S	0.367	0.389	0.359	0.53	0.37	0.378	0.321	0.357	0.336	0.382	0.331	0.359	0.332	0.374	0.329	0.401
	Minivan, Ni-Cd	0.318	0.372	0.318	0.401	0.318	0.385	0.318	0.342	0.318	0.375	0.318	0.339	0.318	0.378	0.318	0.360
	Minivan, Ni-MH	0.317	0.376	0.317	0.406	0.317	0.389	0.317	0.343	0.317	0.379	0.317	0.345	0.317	0.381	0.317	0.362
	F S Van, Na-S	0.604	0.636	0.591	0.867	0.535	0.614	0.526	0.584	0.551	0.620	0.542	0.588	0.544	0.607	0.539	0.654
	F S Van, Ni-Cd	0.515	0.599	0.515	0.642	0.515	0.620	0.515	0.553	0.515	0.602	0.515	0.547	0.515	0.608	0.515	0.578
	F S Van, Ni-MH	0.514	0.605	0.514	0.652	0.514	0.627	0.514	0.555	0.514	0.608	0.514	0.514	0.514	0.614	0.514	0.581

Table 4.3 EV Electricity Consumption in kWh/Mile from Wall Outlets: Including Heating, Cooling, and Thermal Loss (cont'd)

YEARS 2008-2010:																	
		Chicago				Houston				Los Angeles				Washington, DC			
Appliance	Vehicle Battery	Spring	Summer	Fall	Winter	Spring	Sum-mer	Fall	Winter	Spring	Sum-mer	Fall	Winter	Spring	Sum-mer	Fall	Winter
HHold	Mi-Com, Ph-Acid	0.209	0.236	0.209	0.236	0.209	0.242	0.209	0.220	0.209	0.237	0.209	0.217	0.209	0.239	0.209	0.227
	Compact, Na-S	0.355	0.327	0.323	0.488	0.298	0.314	0.288	0.326	0.297	0.318	0.289	0.313	0.296	0.308	0.291	0.362
	Compact, Ni-Cd	0.248	0.284	0.248	0.284	0.248	0.289	0.248	0.263	0.248	0.284	0.248	0.259	0.248	0.286	0.248	0.270
	Compact, Ni-MH	0.241	0.279	0.241	0.281	0.241	0.285	0.241	0.257	0.241	0.279	0.241	0.252	0.241	0.282	0.241	0.265
Fleet	Compact, Na-S	0.262	0.279	0.257	0.349	0.253	0.280	0.248	0.273	0.247	0.276	0.244	0.260	0.271	0.290	0.267	0.324
	Compact, Ni-Cd	0.248	0.284	0.248	0.284	0.248	0.289	0.248	0.263	0.248	0.284	0.248	0.259	0.248	0.286	0.248	0.270
	Compact, Ni-MH	0.241	0.279	0.241	0.281	0.241	0.285	0.241	0.257	0.241	0.279	0.241	0.252	0.241	0.282	0.241	0.265
	Minivan, Na-S	0.310	0.335	0.303	0.466	0.274	0.324	0.269	0.302	0.282	0.327	0.278	0.303	0.279	0.321	0.276	0.348
	Minivan, Ni-Cd	0.261	0.315	0.261	0.347	0.261	0.326	0.261	0.285	0.261	0.317	0.261	0.280	0.261	0.319	0.261	0.307
	Minivan, Ni-MH	0.262	0.319	0.262	0.355	0.262	0.332	0.262	0.288	0.262	0.322	0.262	0.282	0.262	0.325	0.262	0.310
	F-S Van, Na-S	0.511	0.545	0.499	0.759	0.450	0.528	0.442	0.462	0.464	0.532	0.456	0.497	0.458	0.522	0.453	0.567
	F-S Van, Ni-Cd	0.424	0.506	0.424	0.556	0.424	0.526	0.424	0.461	0.424	0.509	0.424	0.453	0.424	0.514	0.424	0.493
	F-S Van, Ni-MH	0.426	0.514	0.426	0.567	0.426	0.536	0.426	0.466	0.426	0.517	0.426	0.457	0.426	0.523	0.426	0.500

Table 4.4 Daily Mileage of EVs (miles/day)

	Chicago	Houston	Los Angeles	Washington, D.C.
Household				
Cars	24.4	26.8	26.8	30.0
Fleet (weekdays only)				
Cars	57	54	61	42
Vans	40	58	48	57

Table 4.5 Battery Capacity (kWh)

YEARS 1998-2002:																	
		Chicago				Houston				Los Angeles				Washington, DC			
Appliance	Vehicle Battery	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Household	2-seater, Pb-Acid	15.0	16.4	15.3	12.9	16.3	16.9	16.3	15.4	15.9	16.5	16.3	15.7	15.5	16.7	15.8	14.1
	Compact, Pb-Acid	16.9	18.6	17.3	14.7	18.4	19.2	18.5	17.4	18.0	18.7	18.4	17.8	17.6	18.9	17.9	15.9
Fleet	Compact, Pb-Acid	16.9	18.6	17.3	14.7	18.4	19.2	18.5	17.4	18.0	18.7	18.4	17.8	17.6	18.9	17.9	15.9
	M Mvan, Na-S	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4
	Minivan, Ni-Cd	16.9	16.9	16.9	16.9	16.9	16.9	16.9	16.9	16.9	16.9	16.9	16.9	16.9	16.9	16.9	16.9
	F-S Van, Pb-Acid	27.0	29.6	27.6	23.4	29.4	30.5	29.5	27.7	28.7	29.8	29.4	28.3	28.0	30.2	28.4	25.4

YEARS 2003-2007:																	
		Chicago				Houston				Los Angeles				Washington, DC			
Appliance	Vehicle Battery	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Household	Mi-Com, Pb-acid	21.3	23.4	21.8	18.4	23.2	24.1	23.3	21.9	22.7	23.5	23.2	22.3	22.1	23.8	22.5	20.0
	Compact, Na-S	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
	Compact, Ni-Cd	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3
	Compact, Ni-MH	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8
Fleet	Compact, Na-S	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
	Compact, Ni-Cd	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3	41.3
	Compact, Ni-MH	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8
	Minivan, Na-S	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7
	Minivan, Ni-Cd	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
	Minivan, Ni-MH	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4
	F S Van, Na-S	62.1	62.1	62.1	62.1	62.1	62.1	62.1	62.1	62.1	62.1	62.1	62.1	62.1	62.1	62.1	62.1
	F S Van, Ni-Cd	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9	56.9
	F S Van, Ni-MH	52.6	52.6	52.6	52.6	52.6	52.6	52.6	52.6	52.6	52.6	52.6	52.6	52.6	52.6	52.6	52.6

Table 4.5 Battery Capacity (kWh) (cont'd)

YEARS 2008-2010:													
Appliance	Vehicle Battery	Chicago			Houston			Los Angeles			Washington, DC		
		Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Household	Mi-Com, Ph-Acid	18.3	20.1	18.7	15.8	19.9	20.7	20	18.8	19.5	20.2	19.9	19.2
	Compact, Na-S	32.1	32.1	32.1	32.1	32.1	32.1	32.1	32.1	32.1	32.1	32.1	32.1
	Compact, Ni-Cd	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1
	Compact, Ni-MH	31.7	31.7	31.7	31.7	31.7	31.7	31.7	31.7	31.7	31.7	31.7	31.7
	Compact, Na-S	32.1	32.1	32.1	32.1	32.1	32.1	32.1	32.1	32.1	32.1	32.1	32.1
	Compact, Ni-Cd	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1
	Compact, Ni-MH	31.7	31.7	31.7	31.7	31.7	31.7	31.7	31.7	31.7	31.7	31.7	31.7
	MiniVan, Na-S	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4
	MiniVan, Ni-Cd	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6
	MiniVan, Ni-MH	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6
Fleet	F-S Van, Na-S	54.8	54.8	54.8	54.8	54.8	54.8	54.8	54.8	54.8	54.8	54.8	54.8
	F-S Van, Ni-Cd	48.1	48.1	48.1	48.1	48.1	48.1	48.1	48.1	48.1	48.1	48.1	48.1
	F-S Van, Ni-MH	44.8	44.8	44.8	44.8	44.8	44.8	44.8	44.8	44.8	44.8	44.8	44.8

Table 4.6 EV and CV Mileage and Energy Use, by Scenario, Year, and Season

Scenario	Season	EV/CV Mileage (million miles)	Electricity Into Vehicles (MWh)	Electricity Into Vehicles (billion Btu)	Electricity from Power Plants * (billion Btu)	RFG into Vehicles (billion Btu)
Chicago 2000-High	Total	208.4	72,741	248.2	261.3	1,166.0
	Winter	47.1	18,618	63.5	66.8	274.5
	Spring	53.0	16,930	57.8	60.8	264.4
	Summer	56.5	20,737	70.8	74.5	355.8
	Fall	51.7	16,457	56.1	59.1	271.3
Chicago 2010-Low	Total	738.6	262,662	896.2	943.4	4,189.0
	Winter	163.9	69,011	235.5	247.9	968.5
	Spring	187.4	60,381	206.0	216.8	951.4
	Summer	202.3	74,059	252.7	266.0	1,306.0
	Fall	185.1	59,211	202.0	212.6	962.9
Chicago 2010-High	Total	3251.5	1,026,687	3,503.1	3,687.5	15,540.0
	Winter	721.9	259,305	884.8	931.4	3,571.0
	Spring	824.8	241,060	822.5	865.8	3,573.0
	Summer	890.2	289,857	989.0	1,041.1	4,776.0
	Fall	814.6	236,465	806.9	849.4	3,617.0
Houston 2000-High	Total	113.9	33,473	114.2	120.2	527.9
	Winter	25.7	7,618	26.0	27.4	119.4
	Spring	29.0	8,044	27.5	28.9	121.4
	Summer	30.9	9,997	34.1	35.9	162.5
	Fall	28.3	7,813	26.7	28.1	124.5
Houston 2010-Low	Total	689.3	230,285	785.7	827.1	3,841.0
	Winter	152.9	51,604	176.1	185.4	845.0
	Spring	174.8	54,661	186.6	196.4	876.8
	Summer	188.8	70,325	240.0	252.6	1,233.0
	Fall	172.8	53,696	183.2	192.8	887.2
Houston 2010-High	Total	2571.0	788,491	2,690.3	2,831.9	12,230.0
	Winter	570.8	177,084	604.2	636.0	2,713.0
	Spring	652.2	189,291	645.9	679.9	2,837.0
	Summer	703.8	236,394	806.6	849.1	3,810.0
	Fall	644.1	185,722	633.7	667.1	2,873.0

*Electricity from power plants is 5% higher than electricity into vehicles reflecting transmission and distribution loss.

Table 4.6 EV and CV Mileage and Energy Use, by Scenario, Year, and Season (cont'd)

Scenario		Season	EV/CV Mileage (million miles)	Electricity Into Vehicles (MWh)	Electricity Into Vehicles (billion Btu)	Electricity from Power Plants * (billion Btu)	RFG into Vehicles (billion Btu)
LA	2000-High	Total	371.9	124,907	426.2	448.6	2,057.0
		Winter	84.1	28,216	96.3	101.4	465.2
		Spring	94.7	30,107	102.7	108.1	471.9
		Summer	100.8	37,299	127.3	134.0	635.5
		Fall	92.3	29,285	99.9	105.2	484.2
LA	2010-Low	Total	5572.3	1,704,245	5,814.9	6,120.9	26,280.0
		Winter	1237.2	373,074	1,272.9	1,339.9	5,862.0
		Spring	1413.5	428,486	1,462.0	1,538.9	6,150.0
		Summer	1525.5	497,466	1,697.4	1,786.7	8,045.0
		Fall	1396.0	405,219	1,382.7	1,455.5	6,227.0
LA	2010-High	Total	13529.0	3,993,218	13,624.9	14,342.0	60,920.0
		Winter	3007.0	871,113	2,972.2	3,128.6	13,610.0
		Spring	3432.8	947,196	3,231.8	3,401.9	14,280.0
		Summer	3701.8	1,156,436	3,945.8	4,153.5	18,550.0
		Fall	3387.6	1,018,472	3,475.0	3,657.9	14,470.0
DC	2010-Low	Total	470.5	162,403	554.1	583.3	2,705.0
		Winter	104.4	38,437	131.1	138.0	605.7
		Spring	119.3	37,852	129.1	135.9	617.2
		Summer	128.9	47,710	162.8	171.4	857.2
		Fall	117.9	38,404	131.0	137.9	624.5
DC	2010-High	Total	1724.3	558,731	1,906.4	2,006.7	8,585.0
		Winter	383.0	130,378	444.9	468.3	2,000.3
		Spring	437.4	131,231	447.8	471.4	2,017.5
		Summer	472.0	161,405	550.7	579.7	2,481.1
		Fall	431.9	135,716	463.0	487.4	2,086.2

* Electricity from power plants is 5% higher than electricity into vehicles reflecting transmission and distribution loss.

Table 4.7 Emissions from CVs, by Scenario, Year and Season

		EMMISSIONS (million tons/yr)					
Scenario	Season	CO2	CO	NMVOC	NOX	SO2	TSP
Chicago 2000-High	Total	183	2.76	0.233	0.194	0.0218	0.00827
	Winter	42.4	0.987	0.0582	0.0492	0.00492	0.00187
	Spring	41.4	0.652	0.0585	0.054	0.00473	0.00205
	Summer	56.5	0.4	0.0574	0.0431	0.00723	0.00224
	Fall	42.3	0.734	0.0587	0.048	0.0048	0.00211
Chicago 2010-High	Total	2371	56.2	4.65	4.72	0.276	0.129
	Winter	535.5	18.4	1.02	1.21	0.0634	0.0286
	Spring	549.1	13.6	1.22	1.16	0.0639	0.0323
	Summer	731.8	9.36	1.23	1.14	0.0841	0.0353
	Fall	554.2	14.8	1.19	1.21	0.0647	0.0327
Chicago 2010-Low	Total	650.6	11.44	0.973	0.979	0.075	0.0293
	Winter	148.3	3.92	0.229	0.254	0.0173	0.00651
	Spring	147.9	2.75	0.251	0.24	0.017	0.00734
	Summer	205.1	1.76	0.247	0.235	0.0234	0.00803
	Fall	149.3	3.02	0.246	0.25	0.0172	0.00743
Houston 2000-High	Total	83	1.08	0.134	0.0914	0.00946	0.00452
	Winter	18.58	0.344	0.0324	0.0225	0.00214	0.00102
	Spring	19.12	0.232	0.0333	0.0223	0.00218	0.00112
	Summer	25.76	0.221	0.0317	0.0234	0.00291	0.00123
	Fall	19.52	0.284	0.037	0.0232	0.00223	0.00115
Houston 2010-High	Total	1910	32.48	4.05	3.67	0.219	0.102
	Winter	418.6	9.9	0.953	0.815	0.0486	0.0227
	Spring	443.2	7.38	1.03	0.83	0.0508	0.0256
	Summer	600.5	6.95	0.942	0.899	0.0683	0.0279
	Fall	447.3	8.26	1.13	1.12	0.0515	0.0259
Houston 2010-Low	Total	604.7	7.45	0.968	0.895	0.0688	0.0274
	Winter	131.7	2.37	0.229	0.202	0.0151	0.00607
	Spring	138.1	1.66	0.244	0.205	0.0157	0.00686
	Summer	195.5	1.57	0.228	0.221	0.0221	0.00749
	Fall	139.4	1.86	0.267	0.267	0.0159	0.00694

Table 4.7 Emissions from CVs, by Scenario, Year and Season (cont'd.)

Scenario		Season	CO2	CO	NMVOC	NOX	SO2	TSP
LA	2000-High	Total	327.4	2.04	0.272	0.206	0.00867	0.0148
		Winter	73.75	0.621	0.0634	0.0488	0.00196	0.00334
		Spring	75.21	0.413	0.0698	0.05	0.00199	0.00366
		Summer	101.6	0.399	0.0635	0.0534	0.00268	0.004
		Fall	76.81	0.615	0.075	0.0537	0.00204	0.00376
LA	2010-High	Total	9624	99.23	9.47	6.69	0.257	0.537
		Winter	2141	27.49	2.01	1.56	0.0574	0.119
		Spring	2260	21.55	2.35	1.64	0.0602	0.134
		Summer	2946	21.44	2.65	1.75	0.0782	0.147
		Fall	2277	28.75	2.46	1.74	0.061	0.136
LA	2010-Low	Total	4134	52.54	4.62	3.41	0.111	0.221
		Winter	917.5	14.19	0.977	0.793	0.0247	0.0491
		Spring	968.6	11.63	1.15	0.836	0.0259	0.0554
		Summer	1273	11.67	1.3	0.892	0.0339	0.0605
		Fall	974.7	15.05	1.2	0.884	0.0263	0.0561
DC	2000-High	Total	126.6	1.6	0.15	0.124	0.0144	0.00573
		Winter	28.09	0.522	0.0331	0.031	0.00323	0.00127
		Spring	29.07	0.381	0.0395	0.0305	0.00331	0.00143
		Summer	40.09	0.265	0.0353	0.0307	0.00452	0.00157
		Fall	29.33	0.434	0.0421	0.0317	0.00335	0.00145
DC	2010-High	Total	1335	25.55	2.43	2.47	0.154	0.0684
		Winter	296.3	7.75	0.494	0.618	0.0346	0.0152
		Spring	308.6	6.21	0.651	0.608	0.0356	0.0171
		Summer	419	4.62	0.59	0.614	0.0476	0.0187
		Fall	311.2	6.98	0.69	0.631	0.0361	0.0174
DC	2010-Low	Total	424.1	6.16	0.594	0.615	0.0484	0.0187
		Winter	93.91	1.96	0.128	0.154	0.0109	0.00414
		Spring	96.63	1.48	0.157	0.151	0.0111	0.00468
		Summer	136.1	1.05	0.141	0.152	0.0154	0.00511
		Fall	97.45	1.68	0.168	0.157	0.0112	0.00474

5.0 Electric Utility Analysis

This section describes the methods and data employed to project the operating characteristics of the electric utility systems that would be used in the years 2000 and 2010 to supply electric power to charge electric vehicles (EVs). (Figure 5.1 shows the energy cycle segments discussed in this section.) The methods used to estimate fuel required to generate electricity and the environmental residuals associated with that generation are described. The analysis involved characterizing the technologies employed within the power systems, and projecting how the whole integrated system of generating units would be operated in a future with and without EVs. By comparing the fuel use and environmental residuals of the utility systems with and without EVs, we can determine the impact that EVs have on power plant emission levels and fuel consumption patterns.

Because we wanted to examine EV use in a "real world" setting, we chose to look at the actual power systems that currently supply the four metropolitan areas chosen for analysis. We attempted to project how those systems would be modified (e.g., by adding additional generating resources) and then operated to handle the additional demand resulting from the increased use of EVs, consistent with the low- and high-penetration EV scenarios explained in Chapter 3.

The operation of an electric power system is a very complex. It involves striking a continuous balance between electricity demand, which changes constantly, and supply of generating capacity, which varies depending on the operating rates of many of generating units. Projecting how utility systems will operate in the future (e.g., in 2000 or 2010) introduces many unknown factors such as the future demand for electricity, the number and nature of new generating units that will be built, and the future price of fuels, which affects the relative cost of operating various types of units, and hence their desirable operating (dispatch) order.

The sections below describe the analysis of future electric utilities that supports the EVTECA. The first section gives a general overview of the approach, and the sections that follow provide an explanation of each of the steps used in the computations. More detail is provided in a series of sections found in Appendix C.

5.1 Overview of Methodology

The first sequence of steps in the approach involves creating a "Base Case" projection of how the utility system would operate in a future without EVs. This is accomplished as follows:

- Step 1. **Project demand:** Estimate future electricity demand (load), including the temporal profile of the load at each time interval during a typical 24-hour day.
- Step 2. **Project supply:** Forecast the total electric generating capacity (energy resources) needed to meet the energy demand, the types and characteristics of the units that comprise that capacity (considering units existing now and new units to be added during the projection periods), and the energy storage capacity; and determine the availability of these resources during the course of the year.

Figure 5.1 Segments within the Electric Vehicle Energy Cycle Discussed in Chapter 5 (shown with dotted lines)

- Step 3. **Project dispatch order:** Given the supply and demand conditions in the two steps above as well as other factors such as projected fuel prices, estimate the order in which the available resources would be called on (dispatched) to meet the demand in each time interval.
- Step 4. **Compute environmental emissions:** Estimate the seasonal electricity output of each unit (based on the dispatching order described in Step 3 and the total demand in each time interval), and considering its emission rate, compute the environmental emissions associated with its use.

The next sequence of steps involves projecting how the Base Case would change if additional demand, resulting from EV use, were introduced into the load profile.¹ The steps are as follows:

- Step 5. **Alter load profile:** Add the additional load resulting from EV use to the Base Case load in each time interval within the profile for the typical 24-hour day.
- Step 6. **Project additional capacity needed:** Based on the change in the load profile from Step 5 above, determine if additional capacity is needed to keep the system within the same system reliability constraints² as it would have been without the additional EV demand. Develop a set of scenarios representing the kinds of capacity (e.g., combustion turbines, combined cycle plants, etc.) that would be used to meet incremental EV load.³
- Step 7. **Conduct new dispatch analysis:** Based on the new configuration of the power system, determine the revised dispatch order based on the operating cost of each unit and other factors.
- Step 8. **Estimate incremental emissions resulting from EV penetration:** Calculate generation and emission changes between EV Scenario and Base Case. Because the dispatch order and level of demand is different in the EV Scenario compared to the Base Case, some of the units may be used more in the EV case than in the Base Case, and some may be used less.

Each of these steps is discussed briefly as follows.

¹ As just described, the first steps in this methodology examined planned additions by the utilities considered the growth in system demand without any EV penetration (as described in the Integrated Resource Plans --or IRPs-- of the utilities), and the second set of steps examined the additional demand resulting from EV use. The resource mix resulting from this two-phased approach may be different from what one would obtain by planning to meet the aggregate load. In the IRP processes used by utilities today, capacity expansion (resource addition) is influenced by the aggregated demand growth, not the incremental demand associated with EVs alone. Consequently, if the utilities had conducted a resource expansion exercise for the aggregate load of EVs and other uses, the resource additions could be different from that obtained by considering the two demands (EV and other) separately. Nevertheless, the methodology used appeared to be the only practical approach to examining incremental emissions associated with EVs. We could not undertake a planning exercise that simulated an IRP process utilities use to project how they will meet the aggregate load, because it would have entailed the collection of vast amounts of data and a very resource-intensive planning exercise. Besides, the data needed are not easily available, and if obtainable, the process would have introduced a high degree of uncertainty. Therefore, we made the estimation incrementally over current utility plans.

² Reliability was measured as expected unserved energy.

³ New units already planned by the utility were taken into account before unplanned units were assumed to be needed.

5.2 Projecting Loads in the Base Case

Each of the four metropolitan areas is serviced primarily by one or two major power companies. Houston is served by the Houston Light and Power Company (HLP). The Washington, D.C. area is served by Potomac Electric Power Company (PEPCO) and Virginia Electric Power (VEPCO).⁴ Southern California Edison Company (SCE) and the Los Angeles Department of Water and Power (LADWP) serve Los Angeles. Consolidated Edison (CE) serves Chicago. For the most part, projections of future demand, temporal profiles, and the other data needed to project power plant operating practices in the future were obtained from these utilities or their regulators. (A majority of the data needed were contained in the integrated resource planning [IRP] depositions of the utilities to their regulators).

Most of the data for the Los Angeles area were obtained from the California Energy Commission. Consolidated Edison provided most of the data for the Chicago area. The data for Houston were obtained from the Texas Public Utilities Commission, and the data for Washington, D.C. area were obtained by BCS Inc., a consulting company in the Washington, D.C. area, based on information from the public utility commission and utilities. In some cases, data were adjusted to make the many required assumptions consistent. Extensive discussions were held with the utilities to seek agreement regarding changes to any data they supplied.

Given the overall demand estimates, temporal load profiles were constructed for weekdays and weekend days within each season. The profiles were developed for one-hour intervals to most closely simulate the way utilities make dispatching decisions on an almost continuous basis. The difference among metropolitan areas reflects the variation in the end uses, e.g., types of industry, the mix of residential versus commercial/industrial load, etc. Developing a temporal load profile involves many assumptions and uncertainties. Details of the development of these profiles can be found in Appendix C.1.

We had to exercise caution to ensure that the forecast of future load under the base case did not include the penetration of EVs. This is particularly true in case of California where zero emission vehicle (ZEV) regulations have stipulated that a certain number of EVs (and other vehicles that can be certified as vehicles with zero emission) should be sold in the year 1998 and beyond. Under those circumstances, EV loads were included in the utilities' projections for the future. We had to subtract this component out; a failure to do so would have resulted in the double counting of EVs from the addition of our projections of EV load.

5.3 Projecting Power Supply in the Base Case

The capacities of existing and planned generating units were obtained from the utilities and regulatory agencies. For the most part, the expansion plans as found in the IRP depositions were used as the input data. However, in some instances, the utility and its regulators have not reached complete agreement in this regard. The disagreement stems from how much capacity can be acquired from nonutility sources, and the need for capacity as influenced by demand side management (DSM) and energy efficiency

⁴ There are three utilities serving the D.C. area: Baltimore Gas and Electric Co. (BGE), Potomac Electric Power Co. (PEPCO), and Virginia Electric Power Co. (VEPCO). BGE serves a very small portion of the Washington, D.C. air basin, and therefore it was excluded from the study.

measures. Based on discussions with the utilities and its regulators, we used judgement in determining the needed generation and which technologies would be employed. Several utilities included in the analysis (SCE, LADWP, CE, VEPCO) have a surplus of capacity, indicating that no additional capacity installations were required in the Base Case (or in the scenario that calls for low penetration of EVs).⁵

Seasonal availability of the existing and planned generating units was also an important factor in conducting the analysis. For the most part, information on factors affecting seasonal availability of resources was obtained from the utilities or regulators. Several considerations factor into the availability of the units: the timing and frequency of nuclear plant refueling, the availability of energy storage facilities, the variation in some resources, such as hydro-power, due to seasonal changes in water flow, etc. These factors are discussed briefly below.

- *Maintenance Scheduling and Refueling of Nuclear Units*

In most cases, the annual maintenance and refueling schedules for the generating units were obtained from the utilities. In other cases, we had to assume some maintenance program for the years 2000 and 2010 (we assumed the constraint of the expected unserved energy margin, computed after shutting the machines down for maintenance, was applicable in all seasons). There is some uncertainty regarding the refueling cycle because the exact time at which a nuclear unit is taken out for refueling depends on its energy production pattern.

- *Energy Storage*

Energy storage on a large scale is possible in pumped storage plants. During periods of lower incremental cost of production (low loads), water is pumped to an upper reservoir. During periods of higher incremental cost of production (peak periods), the stored water is discharged through the turbines to generate energy. Such an operation, which exploits the difference in the cost of production during different time periods, results in net savings. Our research incorporated the simulation of storage operation as outlined in the 1983 paper (Rau and Nesculescu, 1983).

- *Presence of Capacity with Limited Resource Availability*

Some resources within a utility system are limited in their annual or seasonal generation potential. For example, at hydro-electric units, the energy production capability is dictated by the amount of water available. The constraints on these energy resources were accounted for in the analysis.

⁵ Some of the utilities in this study have existing thermal units which are capable of burning different fuels such as natural gas, coal, and oil. For such multi-fueled units, the actual share of fuels that will be used in the future is not very clear. However, in all cases, the share of the second fuel in the 1990–1993 period was very small. Therefore, in our study, we assumed that the energy generated by the dual units was produced using the same primary fuel as in the 1990–1993 period.

5.4 Dispatching Resources to Meet Demand in the Base Case

As discussed above, the demand for electricity by utility customers and the availability of generation resources change constantly. The manner in which resources are dispatched to meet demand strongly influences the air pollutant emissions and the fuels consumed during the course of the system operation, because the individual units vary in their fuel type, energy efficiency, and emission rate.

In this analysis, two basic methods were used to determine each utility's future dispatching order (the order in which the various generating units are brought on line and operated to meet the demand). The two methods are the merit order (least-cost) dispatch and the emission-constrained dispatch.

In operating practice, most utilities dispatch the available generating resources to minimize cost. The object of the dispatcher is to minimize costs by allocating the energy output from different units at different times of the day or season. Additionally, a utility engages in the sale and purchase of energy. Based on contractual obligations, the dispatcher allocates the sales and purchases to appropriate times of the day or season. The ordering of machines according to the incremental cost of energy production is called the merit order. Machines with higher incremental cost used to serve higher demands are called machines of higher merit order. Machines higher in the merit order generate energy for a shorter period during the day; hence, their load factor is lower than the machines lower in the merit order. Consequently, machines that are very high in the order are used only during peak load periods. As a consequence, the incremental cost of energy production in the system is a non-decreasing function of demand.

The incremental cost (\$/MWh) associated with a each generating unit is a function of its fuel cost and other operating costs. For Chicago, the expected fuel prices, as forecast by CE and its regulators, were used in our study. For the other cities, we used the projections of the Energy Information Administration (EIA, 1993). Non-fuel operating costs were obtained from the utilities.

Merit order dispatch was assumed to apply in all metropolitan areas in our study, and in Chicago, another dispatch approach was also examined. The dispatching of the Commonwealth Edison system in Chicago is the one most likely to be affected by provisions in the Clean Air Act Amendments of 1990 (CAAA) that require plants to limit SO₂ emissions from high-emission units by either installing control devices or curtailing the generation (and hence emission levels) to a specified level. Thus, in addition to a merit-order dispatch in Chicago, we also assumed a dispatch based on an order that would allow the system to reach compliance with the CAAA.

A more detailed description of both the merit-order and emission-constrained dispatching approaches used in this analysis can be found in Appendix C.2, and an example of how the approach is applied is found in Appendix C.4.

5.5 Calculation of Emissions from Generating Units in the Base Case

The criteria pollutant average emission rates in lb/mmBtu were also obtained from the utility companies when possible. In the cases where some or all of the emissions rates were not available, we assumed values based on the emission rates of generic units, considering the unit's age and technology. Emissions were simply calculated by multiplying the emission rate (NREL, 1993) by the fuel input of the power plant. For units projected by the utilities to be on line in the projection period, but which are currently not built, standard technology characterization data (EPRI, 1993) were used to estimate emission rates.

5.6 Simulation of Load Curves Associated with Electric Vehicles

Section 4.1.3 (in the Vehicle Analysis chapter above) describes the assumptions that led to the estimates of hourly electricity demand for the electric vehicle scenarios. The methodology takes into account the following factors: (1) the battery recharge profiles,⁶ (2) a distribution of the depths of discharge (DOD) of the batteries when they are plugged in for recharging, (3) a distribution in the starting times that the batteries are plugged in for recharging (the distribution was created for five-minute intervals). These factors were analyzed for each battery type, and then for a given projection year and scenario, the hourly recharge requirements for the various vehicle and battery types were combined to make an estimate of the total hourly electricity requirements for battery recharge. The EV high- and low-penetration cases assume that fleet vehicles are charged between 4 p.m. and 6 p.m., and that household vehicles are charged when the vehicles users arrive home.⁷ Sensitivity runs were made (called the "policy cases") in which the charging occurred at different times of the day.

The basic data on recharge profiles, DOD distribution, and plug-in time (described in Section 4.1.3) were employed in a model used to simulate the charging loads of EVs. The basic approach used in the model, which mimics the logic described in Section 4.1.3, is described in Appendix C.4. The model assumes a uniform distribution of battery "plug-ins" across each hour, so that the dispatching calculations, which are performed in five-minute increments, can be carried out.

The EV demand curve is added to the base case demand curve to obtain a new total demand curve. This is illustrated in Figure 5.2, which shows the system demand in Chicago in 2010 (aggregated to hourly values) with and without EV charging. Based on the new demand curve, the need for capacity additions is assessed, as described in the next section.

5.7 Projecting Additional Capacity Needs Associated with Electric Vehicle Scenarios

New capacity needs were projected on the basis of expected unserved energy (EUSE).⁸ For the base case, the model computed the EUSE given the load without EVs and the capacity additions planned by the utility. Additional capacity was added in the EV case until the EUSE was equal to its base-case level.

For the high-penetration cases studied, all utilities needed additional capacity to maintain the same level of reliability as in the base case. It is difficult to predict what types of generating equipment will be added to meet the EV demand. For instance, it is unclear how much of the needed capacity will be supplied by in-basin Independent Power Producers (IPP) or from other sources outside the region through the wholesale wheeling power. However, to proceed with the analysis, assumptions were made, as described below in this section.

⁶ The battery recharge profile shows the hourly electricity input over a specific length of time needed to recharge a battery.

⁷ The distribution of when the vehicles arrive home was based on 1990 NPTS data. Most trips end between 3 p.m. and midnight.

⁸ EUSE is the statistical expectation of the energy demand that will not be met by the schedule generating units, given probabilistic representations of system load and unit availability over time.

Figure 5.2 Chicago Winter 2010 Peak Day Temporal Demand With/Without EV Unconstrained Charging

It is our understanding that electrical equipment manufacturing industry currently prefers combined cycle (CC) generating units as the most economical choice for the future. These are usually natural-gas-fired modular units which are highly efficient (about 50%). Another promising technology is the Integrated Gasification Combined Cycle (IGCC) technology in which coal is gasified before combustion. These technologies have a short construction time and are clean-burning. On the other hand, utilities in the past that needed peaking capacity installed combustion turbines (CTs). Such units are also fueled by natural gas or oil, are clean-burning, and have a short construction time, but they are less efficient than the CC or IGCC units and hence are not economical to supply base load. They are usually dispatched to supply peaking loads for a few hours during the day.

In order to examine the extremes of the spectrum of possibilities, we examined CC⁹ units and CT units as two possible options. As stated earlier, both these technologies have low emissions, but the CC units have a lower cost of energy production. Consequently, if CC units are chosen, in addition to supplying the new EV load, they will be dispatched to serve system loads during noncharging hours. On the other hand, a choice of CTs will mean that they will not be dispatched to meet system loads other than those during peak hours.

The heat rates for the future CC and CT generators were taken from a generic unit from the EPRI Technical Assessment Guide (EPRI, 1993). The emission rates for these units were taken from the Environmental Characterization Database (NREL, 1993).

Renewable resource additions, such as wind, photovoltaic (PV), solar thermal, and biomass, were also considered. None of the IRP submissions of the utilities we examined include further addition of such resources beyond the mid-1990's. A full scale resource expansion simulation is complicated by the issues discussed in the section on expansion plans. Additionally, if one were to consider intermittent renewable resources (IR), the IRP process would require information on the availability of renewable energy resources, which is site-specific for intermittent technologies. Since the dispatch of energy in the system depends on the temporal nature of wind output, for a proper simulation of the dispatch procedure, one has to know the actual sites under consideration, and the resource data for that site. Such data are not available.

Even if the data were available, the inclusion of such resources in a resource plan is not a simple matter. For example, if 100 MW from CT units were required to maintain reliability with the additional demand of EVs, much more than 100 MW of installed capacity would be required to provide the same reliability with wind capacity. As an extreme example, if the wind output is not at all correlated with the demand of EVs, no amount of installed wind capacity will be able to meet the load with the same degree of reliability unless one installs some form of energy storage. Installation of storage adds to the capital cost and may make the renewable option unattractive.

Therefore, the option of adding renewable technologies was not considered a strong possibility in the time horizon of our study. Consequently, we did not include renewables in our scenario analyses.

⁹ In the case of CE, we added IGCC technology because this was their choice as indicated by their resource expansion plan.

5.8 Conducting Dispatch Analysis for the Electric Vehicle Scenarios

The dispatch analysis for the EV Scenarios was conducted in the same manner as that of the Base Case (see Section 5.4.) The merit order of the units almost always changes between the Base Case and the EV Scenarios because new units, with different incremental costs, have been introduced into the system. In most cases, the new units have very high efficiencies and, therefore, their operating costs are lower; hence the incremental cost of a unit of electricity is lower if it is supplied by that new unit. The generation from each unit in the system was estimated, based on their merit order.¹⁰

5.9 Estimating Incremental Emissions Associated with Electric Vehicle Demand

As described in Section 5.5, the Base Case simulation for a particular year assumed no EV charging took place. The subsequent computations of generation and emissions from each generating unit in the affected utility systems accounted for the total number of EVs present at some future year. When the EV scenario emissions for a particular year and utility system are subtracted from the Base Case emissions, the total resulting tonnage of emissions from the EVs is derived. In this report, the tonnage is called the **incremental system emissions (ISE)**. Using the approach described above, a large penetration of EVs in some future year results in new generating capacity that did not exist in the Base Case. The new generators added to meet the demand of EVs are also dispatched to meet the original (native) load of the system. Consequently, the change in system emissions that results from the penetration of EVs is not only from the charging of the EVs, but is also from the re-dispatching of both the original and the added generating units to meet the native load. Therefore, the ISE indicate the change in the total system emissions arising from the planning of the utility system to accommodate a certain number of EVs in the future. The units of ISE are tons; ISE can be positive or negative.

We also explored other ways of accounting for utility-related emissions associated with EV scenarios. For instance, we calculated marginal and average emissions. (These emissions are discussed in Appendices C.4 and C.5). However, we believe the focus of the assessment should be placed on the ISE emissions because they most appropriately capture the overall effect of EVs on the emissions of the affected utility systems. (See Appendix C.5.)

A full description of the results of the utility analysis also can be found in Appendix C.5.

5.10 References for Chapter 5

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¹⁰ The generation values computed did not account for transmission and distribution (T&D) losses. After the dispatch analysis was completed, the results were scaled to simulate a 5% increase in generation needed to replace T&D losses. The value of 5% was chosen as representative of future T&D losses in the applicable regions; the value for T&D losses was not assumed to vary among regions. In addition, the results presented in Appendix C show electricity generation values close to, but not exactly equal to, the electricity demand for EVs presented in Appendix B. The utility simulation approximated the demand, but did not exactly meet the target. In addition to adjusting the utility results to include T&D losses, the final TEMIS results for the EVTECA also adjusted the utility results such that demand for electricity by EVs exactly matched supply of electricity by utilities (after losses in T&D). The adjustment was made by equally scaling generation from all incremental generating units.

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6.0 Processes Involved in the Production and Delivery of Gasoline

This chapter characterizes the major processes associated with the production of reformulated gasoline (RFG) and describes the assumptions made about these processes in the EVTECA. Separate subsections are dedicated to: crude oil extraction, crude oil transportation, crude oil refining, oxygenate production, and RFG transportation. (Emissions associated with the fuel formulation [mixing] process are considered negligible.) The processes included are shown with a dotted line in Figures 6.1 and 6.2. In addition to these major processes, RFG production also requires natural gas input to the oxygenate production process. The natural gas fuel cycle is described in Chapter 7. Each of the sections below follow the following format: (1) processes involved in the major process are described, (2) the manner in which the processes were characterized in the EVTECA is documented, and (3) the way the processes were configured, i.e., the "scenario information" is explained (when applicable).

A major source for the development of the emissions factors related to RFG production was *A Comparative Analysis of the Environmental Outputs of Future Biomass-Ethanol Product Cycles and Crude Oil/Reformulated Gasoline Production Cycles* (Tyson et al. 1993). Energy content values for RFG and its constituents were taken from the ANL document, *Energy and Crude Oil Input Requirements for the Production of Reformulated Gasolines* (Singh et al. 1993).¹

Other aspects of the RFG production process were characterized using information available in the literature. No attempt was made to provide new research as part of this effort. Most of the analyses used in compiling these emission factors were generalized, using simplifying assumptions, and are intended to define a composite industry rather than the individual processes constituting the industry.

Tables 6.1 and 6.2 summarize the inventory of inputs, outputs, and emissions for crude oil production and crude oil refining, the major inputs (along with natural gas) to RFG production. The individual processes involved in this segment are described below.

6.1 Crude Oil Production

Processes Involved in Crude Oil Production

Crude oil production consists of drilling, extraction, and onsite preparation of the crude oil. Production is influenced by reserve availability, drilling and recovery technologies, and crude oil prices. After oil has been discovered and the reservoir characterized, production can begin. The most common drilling technology is a rotary rig, which cuts and crushes rocks as it descends. Drilling fluid, referred to as drilling mud, is pumped down the well to push cut rocks out of the way and to keep the drill bit cool. In onshore operations, a rig usually drills a single vertical well. However, in recent years there has been an increase in horizontal drilling activity, which reaches the more difficult to access areas. Offshore drilling methods are similar but are adapted to meet different operating conditions.

If there is sufficient pressure, the oil will flow up the well on its own. When this does not happen naturally, artificial pressure is provided by pumps. When these techniques are no longer effective, secondary or tertiary oil recovery methods are often used. Secondary oil recovery usually involves the injection of

¹ The heating value of RFG used in this study is 115,400 Btu/gal.

water or gas into the reservoir to maintain pressure. Tertiary production, sometimes known as enhanced oil recovery, refers to several methods used to extract crude oil from a field once primary production techniques are no longer economic. These methods can be classified as thermal, gaseous, chemical, and microbial.

Once extracted, the mixture of crude oil, water, and gas is separated in special equipment such as heater treaters. Sediment removal or chemical treatment may be necessary to remove unwanted gases, especially when secondary and tertiary recovery methods are implemented.

EVTECA Process Descriptions and Assumptions

Crude oil extraction and transportation operations are characterized based on domestic practices, referenced to the 2010 time frame.² Table D.1.1 in Appendix D.1 presents the national average inventory for the production and processing of both oil and gas products in the oil field. Inventory estimates are based on Tyson et al. (1993), with the exception of carbon dioxide and methane emissions. Carbon dioxide and methane emissions were derived from a detailed analysis of oil and gas field operations and their associated emissions. The values derived in this fashion are more consistent with estimates found in other sources for fossil fuel extraction emissions. The sources used in this study include the U.S. Environmental Protection Agency (EPA 1995, EPA 1992) for emission factors and the U.S. Department of Commerce (DOC 1995) for fuel consumed in oil and gas wells. A more detailed description of the estimation methodology can be found in Chapter 7 (Section 7.2.1).

6.2 Crude Oil Transportation

Processes Involved in Crude Oil Transportation

Transportation of crude oil begins from oil storage near the wellhead. Domestically-produced crude is either transported from storage by an overland pipeline network to a marine bulk terminal storage facility, or is transported by barge/tanker, rail car, tank truck, or overland pipeline directly to the refinery. For example, most crude produced on Alaska's North Slope is transported via pipelines to Valdez and is then transported to the U.S. West and Gulf Coast ports via large ocean tankers. Marine terminals also receive imported crude from international ocean tankers.

The crude collected at the marine terminals is delivered to the refineries via tankers, barges, and pipelines. Tanker trucks are used to transport crude from very remote sites and represent less than three percent of the domestic crude received by refineries. Because regionally specific data were not available, national average modal distributions were used. Transportation distances, by mode, are also based on national average values.

² The EVTECA allocates emissions from oil/gas production between the crude oil and natural gas produced. The emissions allocations are based on the energy content of produced oil and gas, and hence emissions factors for oil and gas from oil wells are the same for both products when expressed in terms of the quantity of emissions per unit energy production. In the year 2010, crude oil is expected to account for 61.5% of the energy value of crude oil well products.

EVTECA Process Descriptions and Assumptions

Electricity consumption and emission factors for crude oil transportation modes are taken from DeLuchi (DeLuchi 1991) and are based mostly on AP-42 (EPA 1995). Emission factors for all crude transportation modes are presented in Appendix D.1, Tables D.1.2 to D.1.6.

Scenario Information

Crude transportation splits by mode were derived from DeLuchi (1991) based on average haul distance estimates and reported ton-miles of crude oil transported. Transportation distances are also from the same document, except for barge transport, which is from Davis (1994). The most important modes of crude oil transport are pipelines and barges, each of which accounts for more than 38% of crude oil transport. Ocean tankers account for 20.3%, and trucks and trains account for 2.9% and 0.2% respectively. Transportation distances are 9,552 miles for ocean tankers, 993 miles for barges, 824 miles for pipelines, 530 miles for trains, and 75 miles for trucks (DeLuchi 1991). The transportation distance for trains is taken from estimates for coal transportation distances, however because of the small fraction of crude oil transported by train, this approximation will have little impact on the inventory results.

6.3 Crude Oil Refining

Processes Involved in Crude Oil Refining

Petroleum is the principal energy source in the U.S. In 1989, about 42% of the total energy consumed in the U.S. came from petroleum. At the beginning of 1990, the operating crude distillation capacity of U.S. petroleum refineries was 15.6 million barrels per day (MMBD) from 205 operating refineries. These refineries ranged in size from small refineries able to process 1,000 barrels of crude per day to those processing more than 400,000 barrels per day.

The refining industry uses crude oil to produce finished products. There are a variety of refinery processes which transform the crude into the wide range of products used in transportation, home heating, lubrication, and other applications. The first phase in refinery processing is atmospheric distillation, where heat separates the various hydrocarbon components of crude by their boiling points. The streams of material from the distillation unit can be used as finished products or as feedstocks for the downstream processes. Downstream processes include vacuum distillation units, "cracking" units that use heat, pressure, or catalysis to increase the yields of lighter products, "reforming" units that upgrade low octane naphthas to a high octane gasoline product called reformate, and process units that combine molecules to yield products with specific properties. Some refineries have operations to pretreat feedstocks, remove impurities, and enhance product characteristics, while others operate specific and limited processes.

EVTECA Process Descriptions and Assumptions

While many products originate from crude in the refinery, this study focuses on the production of residual oil and gasoline blendstocks for the production of reformulated gasoline (RFG). Emissions estimates are derived from Tyson et al. (1993) with the exception of methane emissions which were derived from API data (API 1992). As with crude oil, energy use and emissions from refining are allocated to refinery products based on the energy value of the products. When expressed in terms of the quantity of

emissions per unit energy output, the emissions factors are the same regardless of the product type. Emissions factors for refinery products are presented in Appendix D.1, table D.1.7.

6.4 Oxygenate Production

Processes Involved in Oxygenate Production

Following the production of gasoline blendstocks by the base refinery operations, the gasoline blendstocks are blended or mixed with an oxygenate in order to generate the final RFG fuel formulation. Oxygenates are used to meet a requirement established by the Clean Air Act Amendments (CAAA) of 1990 that all reformulated fuels must have a minimum 2.0% oxygen content. A variety of oxygenates are currently being used or considered (e.g., MTBE, ETBE, and ethanol). MTBE is the oxygenate of focus for this analysis, though the production of ethanol was also characterized.

EVTECA Process Descriptions and Assumptions

There are multiple chemical process routes that can be used to produce MTBE. In this analysis, butane and methanol feedstocks are both derived from natural gas feedstock. Subsequently, the butane and methanol feedstocks are reacted to form MTBE. All MTBE production is assumed to occur at a facility located offsite from the reformulated gasoline refinery. At the refinery, gasoline blendstocks are mixed with the incoming MTBE to create the final reformulated gasoline product.

Process emissions and energy requirements associated with production of the two inputs (butane, methanol) were based on estimates from the Greenhouse Gas Model of M. DeLuchi (June 1996 version). (See Tables D.1.8 and D.1.9 in Appendix D). DeLuchi does not provide estimates of energy and emission from the production of MTBE itself. A report by Stork et al. (1995) provides estimates of MTBE plant energy requirements, which were used in the EVTECA (see Table D.1.10). (The contention by Stork et al. that energy use in MTBE production is offset by byproduct credits was not considered in the EVTECA.)

6.5 RFG Transport

Processes Involved in RFG Transport

The domestic distribution system for RFG is composed of a variety of modes of transportation. Gasoline leaves the refinery by barge, tanker or pipeline. The gasoline may be transported by barge or tanker to a marine bulk storage terminal or by pipeline to a pipeline bulk storage terminal. It is then delivered to bulk plants by tanker trucks, which constitute the majority of the modes of conveyance for the secondary system. Tanker trucks also deliver gasoline from the bulk plants to retail outlets.

EVTECA Process Descriptions and Assumptions

Emissions factors for truck and pipeline transportation of RFG were taken from emissions estimates for crude oil trucks and pipelines, which are shown in Appendix D, Tables D.1.2 and D.1.6, respectively.

Scenario Information

For the two cities included in this study, Houston and Washington, D.C., the RFG transportation modes and distances are estimated based on a simplified model of the transportation process. Shipments data for RFG between Petroleum Administration for Defense District (PADD) III (which includes the Gulf Coast) and PADD I (which includes Washington, D.C.) show that more than 90% of RFG is transported via pipeline (DOE 1996). In addition, roughly half of the total supply of RFG in PADD I is produced in PADD I. RFG transportation emissions and energy use for Washington D.C. are estimated on the basis of pipeline transport, with 50% traveling 218 miles within PADD I, and 50% traveling 1,423 miles from PADD III to PADD I. Because of the short distance from Houston to the Gulf Coast, transportation of RFG is assumed to be by truck, with a total transportation distance of 53.4 miles.

6.6 Other Processes

Fuel formulation (Segment 6 in Figure 6.1) and fuel oil transportation from the refinery to the power plant (Segment 8 in Figure 6.2) were not characterized in this assessment.

6.7 References for Chapter 6

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Tyson, S., et al., National Renewable Energy Laboratory (NREL), *Fuel Cycle Evaluations of Biomass-Ethanol and Reformulated Gasoline, Volume I*, NREL/TP-463-4950, (November 1993a).

Stork, K. And M. Singh. *Impact of the Renewable Oxygenate Standard for Reformulated Gasoline on Ethanol Demand, Energy Use and Greenhouse Gas Emissions*, ANL/ESD-28 Argonne National Laboratory, Argonne, IL. (April 1995).

Figure 6.1 Segments within the Conventional Vehicle Energy Cycle Discussed in Chapter 6 (shown with dotted lines)

Figure 6.2 Segments within the Electric Vehicle Energy Cycle Discussed in Chapter 6 (shown with dotted lines)

**Table 6.1 Inputs and Outputs of the Entire Crude Oil
Production Process***

	Value of Inputs or Outputs per 10 ¹² Btu of Crude Oil Production
Inputs	
1 crude oil	1000000 Mbtu
2 electricity	3530 MBtu
3 fuel oil #6/7	2900 MBtu
4 fuel oil #2/4	115 MBtu
Outputs	
<i>Products</i>	
5 crude oil	1 x 10 ¹² Btu
<i>Airborne Residuals</i>	
6 NO _x	30700 lb
7 SO _x	6210 lb
8 CO	6540 lb
9 Pb	N.I.
10 PM-10	N.I.
11 TSP	874 lb
12 CO ₂	3460000 lb
13 CH ₄	154000 lb
14 NMVOCs	5710 lb
15 N ₂ O	13.4 lb

* Includes domestic oil production and transportation plus supporting electricity, natural gas, fuel oil, and coal segments (a total of 43 processes). The values represent national average U.S. production of crude oil.

N.I.: Not Included
Mbtu: million Btu

Table 6.2 Inputs and Outputs of Oil Refining

	Value of Inputs or Outputs per 10 ¹² Btu of Petroleum Products Produced
Inputs	
1 crude oil	1000000 MBtu
2 electricity	3890 MBtu
3 natural gas	43000 MBtu
Outputs	
<i>Products</i>	
5 petroleum products	1 x 10 ¹² Btu
<i>Airborne Residuals</i>	
6 NO _x	42200 lb
7 SO _x	25600 lb
8 CO	4850 lb
9 Pb	N.I.
10 PM-10	N.I.
11 TSP	1330 lb
12 CO ₂	17400000 lb
13 CH ₄	N.I.
14 NMVOCs	2500 lb
15 N ₂ O	N.I.

N.I.: Not Included

7.0 Processes Involved in the Production and Delivery of Electricity

Four energy cycles for the production of electricity are characterized in this chapter: coal, natural gas, nuclear, and hydroelectric. Fuel oil is also used in production of electricity. The processes involved in fuel oil production (from crude oil extraction through refining) are described in Chapter 6. The processes discussed in this chapter are shown with a dotted line in Figure 7.1. For hydroelectric power, a brief description of the technology is included below, but information on the environmental residuals of this technology are not included. (Air pollutants, which are the focus of this study, are not produced in significant quantities from hydroelectric plants.) The evaluation of the major energy, materials, and environmental inputs/outputs for the three remaining fuel cycles is described below.

The inventory estimates for the utility fuel cycles were developed based in an extensive literature review. The Department of Energy sponsored Oak Ridge National Laboratory (ORNL) and Resources for the Future (RFF) to conduct a series of utility energy cycle studies. While the final results of this work were not yet available at the time this study was initiated and have not been used in this report, a number of the primary documents used by the ORNL/RFF team in conducting their preliminary assessments (ORNL/RFF 1992) were consulted. M.A. DeLuchi, of the University of California, Davis, completed a comprehensive review of alternative transportation energy cycles in 1991 that includes an assessment of electricity production for use in EVs (DeLuchi 1991). Many of DeLuchi's primary sources were reviewed in the process of preparing this analysis. Finally, assorted DOE and EPA documents were consulted for data on various energy cycle processes, including DOE technology characterization documents (DOE 1983; DOE 1988) and EPA's AP-42 document, which includes emission factors for many of the processes described (EPA 1995a).

7.1 Coal Extraction, Processing and Transportation

Coal production in the United States varies among regions in extraction methods, mineral processing, and transportation requirements for both the raw material and processed coal. Table 7.1 presents the inventory data for coal consumed in each of the three utilities modeled in this study: Potomac Electric Power Company (PEPCO), Virginia Electric Power Company (VEPCO), and Houston Light & Power (HL&P) Company. A description of the coal production process and data sources for the estimates used in the study follows.

7.1.1 Coal Extraction and Processing

Processes Involved in Coal Extraction and Processing

Approximately 60% of all coal mined in the United States comes from surface mines, which is the dominant mining technique used in the Western U.S. and Interior U.S. (EIA 1989). Mining operations use bulldozers, loaders, drills, shovels, draglines, and excavators for moving large quantities of overburden and for extracting the underlying coal. This equipment consumes diesel fuel or, in some cases, electricity. Underground mining comprises the remainder of coal mining activities in the U.S., and is utilized primarily in the Eastern U.S. (primarily Appalachia) and portions of the Interior U.S. Because the majority of mining operations occur underground under conditions of restricted ventilation, much of the mining equipment is electric.

Figure 7.1 Segments within the Electric Vehicle Energy Cycle Discussed in Chapter 7 (shown with dotted lines)

**Table 7.1 Data for Coal Extraction, Processing, and Transportation for
Potomac Electric Power Company, Virginia Electric Power Company
and Houston Light & Power Company***

	Inputs/Outputs per 10 ¹² Btu		
	Potomac Electric Power Company	Virginia Electric Power Company	Houston Light & Power **
Inputs			
1 coal	1000000 Mbtu	1000000 MBtu	1000000 Mbtu
2 fuel oil 2/4	4800 Mbtu	7150 Mbtu	39300 Mbtu
3 electricity	6080 Mbtu	6080 Mbtu	2410 Mbtu
Outputs			
4 coal	1 x 10 ¹² Btu	1 x 10 ¹² Btu	1 x 10 ¹² Btu
5 NO _x	21400 lb	24100 lb	75100 lb
6 SO _x	3010 lb	3970 lb	13900 lb
7 CO	5390 lb	6910 lb	20900 lb
8 Pb	0	0	0
9 PM-10	0	0	0
10 TSP	1640 lb	1940 lb	6930 lb
11 CO ₂	1600000 lb	1970000 lb	6490000 lb
12 CH ₄	641000 lb	642000 lb	929 lb
13 NMVOCs	2510 lb	3180 lb	11400 lb
14 N ₂ O	20.6 lb	32 lb	121 lb

MBtu: Million Btu

* Data are for 2010 and include coal extraction through delivery to the plant gate.

** Uses subbituminous coal as input; others use bituminous coal.

Note: The analysis neglects raw coal lost during processing and shipping.

Once mined, coal can be cleaned to upgrade its quality and heating value by removing or lowering quantities of sulfur, rock, clay, and other ash-generating material. About two-thirds of the Eastern coal destined for power plants is cleaned, whereas the majority of Western coal is only crushed and screened before delivery to the plant (EIA 1989). Cleaning is accomplished via wet methods (hydraulic, dense medium, or flotation techniques) or pneumatic (dry) methods that use air flow separators to remove impurities. Once cleaned, the coal is then dried for shipping, usually employing conventional dewatering techniques (vibrating screens, centrifuges, and filters).

EVTECA Process Descriptions and Assumptions

Inventory data for the various coal mining processes are presented in Appendix D.2. The primary sources of data for coal mining (the major exception being methane emissions estimates) are U.S. DOE studies (DOE 1993, 1988) which include detailed information for Eastern surface and underground coal mines, and Western surface coal mines. These data are presented in Tables D.2.1 through D.2.3 (Appendix D.2) in terms of tons of coal output. To account for variations in coal types, the data in Tables D.2.1 to D.2.3 are converted to inputs and emissions per unit energy production using heating values of 12,250 Btu/lb for bituminous coal, 10,200 Btu/lb for subbituminous coal, and 7,300 Btu/lb for lignite coal. Heating values assumed for all fuels in the EVTECA are shown in Table 7.2. The resulting nine tables (D.2.4 to D.2.12) thus present inventory data for coal mining as a function of region (east and west), coal type (bituminous, subbituminous, and lignite), and mine type (surface and underground).

**Table 7.2 Heating Values
Assumed for Various Fuels**

Fuel	Heating Value
Coal-Lignite	7300 Btu/lb
Coal-Subbituminous	10200 Btu/lb
Coal-Bituminous	12250 Btu/lb
Fuel Oil 1	128100 Btu/gal
Fuel Oil 2/4	131800 Btu/gal
Fuel Oil 6/7	138400 Btu/gal
Gasoline Blendstocks	115400 Btu/gal
MTBE	93528 Btu/gal
Natural Gas	21000 Btu/lb
RFG*	11540 Btu/gal
Crude Oil	138400 Btu/gal

* With MTBE, 2% oxygen content

Emission factors for methane are based on DOE estimates of greenhouse gas emissions (DOE 1995), which are presented as a function of mine type (surface or underground). As with other inventory data, these values are converted from emissions per ton of coal produced, to emissions per unit energy production using the energy content of the various coal types given above.

7.1.2 Coal Transportation

Processes Involved in Coal Transportation

Roughly 60% of all coal is transported by rail in the United States, over half of which is carried in dedicated trains (called "unit trains") rather than integrated into a commercial freight trains (EIA 1989). Twenty percent is transported via barges and ships along rivers (e.g., the Mississippi and its tributaries), the Great Lakes, and tidewater areas. Trucks are used for moving coal short distances (less than 50 miles) and in challenging terrain (e.g., Appalachia) and carry roughly 10% of the nation's coal shipments. Finally, the approximate 10% remaining is transported via aerial tramways and conveyers, which are used for very short distances where the mine and plant are in relatively close proximity (so-called "minemouth" power plants). Also, a very limited quantity of coal is transported in the nation's only coal slurry pipeline in northern Arizona/southern Nevada which carries a mixture of coal and water a distance of 273 miles between the coal mine and power plant (DOE 1989).

EVTECA Process Descriptions and Assumptions

Emissions factors for the modes of coal transport included in the EVTECA (trucks and trains) were taken from DeLuchi (DeLuchi 1991) and are based primarily on AP-42, with some adjustments. Energy consumption estimates were also taken from the same source. These values are presented in Appendix D.2, Tables D.2.13 (trucks) and D.2.14 (trains). These are the modes of transport used to bring coal to the Houston and D.C. metropolitan areas.

Scenario Information

In this study, transportation modes and distances were based on detailed analysis of mine types (surface and underground), coal types (subbituminous, bituminous, and lignite) and transportation modes (rail, barge, and truck) at the region, utility, and plant level. Mine type information for Houston and Washington D.C. was developed from DOE (1989). Coal types for the plants in the various EV scenarios were taken from the utility dispatch simulation results. The percentage of shipments, by mode, and average haul distance estimates, by mode, were developed from information obtained from RDI (Colorado School of Mines), for the utilities in Houston (HL&P) and Washington, D.C. (VEPCO and PEPCO).

For Houston, the only coal type called for from the dispatch simulations was subbituminous coal. All of this coal was found to be transported by rail, with 80% from surface mines and 20% from underground mines. Lacking additional data the surface mined coal was assumed to come equally from Eastern and Western mines. Based on the RDI data, the average transportation distance was estimated at 2,067 miles.

For Washington, D.C., the only coal type called for from the dispatch simulations was bituminous coal. For VEPCO, 82% of coal use was found to be transported by rail, and 18% by truck, with average transportation distances of 693 miles by rail and 50 miles by truck. For PEPCO, 100% of coal was found to be transported by rail, with an average transportation distance of 424 miles. For both utilities, the coal was estimated to be 80% from underground mines and 20% from surface mines.

7.2 Natural Gas Extraction, Processing and Transmission

Though the production stages and fuel qualities of natural gas vary by region, it is difficult to characterize natural gas consumed in any particular region by its source. In this analysis, the inventory data for natural gas is developed from national average practices. Table 7.3 presents the aggregated inventory data for natural gas production. The natural gas production process, and sources of data for characterizing the process, are described below.

7.2.1 Natural Gas Extraction

Processes Involved in Natural Gas Extraction

Approximately 90% of the natural gas consumed in the U.S. is produced domestically, the majority of which (74%) comes from dedicated gas wells (DOE 1993b). The remaining production is derived from oil well operations, since many oil deposits contain sufficient concentrations of natural gas to make collection economically attractive. Seventy-one percent of gas extracted from dedicated gas wells is produced at onshore wells, while an even larger percentage of gas from oil wells (89%) comes from onshore operations (DOE 1992). Natural gas is the primary fuel consumed in these activities, although small quantities of diesel are used for drilling.

EVTECA Process Descriptions and Assumptions

Energy use and emissions associated with natural gas extraction in this study are based on two sources of natural gas: dedicated gas wells, and gas co-produced from oil wells. Inventory data sources for gas co-produced from oil wells are described in Chapter 6, and inventory estimates are presented in Appendix D.1, Table D.1.1. Analysis of dedicated gas wells included a detailed review of existing literature on the field production of natural gas.

For this study, field production of natural gas is defined according to the 1993 EPA Report to Congress on Anthropogenic Methane Emissions (EPA 1993a) as the withdrawal of raw gas from underground formations using wells, but also includes emissions from heaters, separators, and dehydrators used in the field production segment. Also included is fuel from the category Lease Fuel as reported in the EIA's Natural Gas Annual (DOE 1995b). Lease fuel is defined as natural gas used in well, field, and lease operations (such as gas used in drilling operations, heaters, dehydrators, and field compressors).

Because most of the lease fuel consumption data for natural gas field production is combined with fuel consumption at oil wells, fuel use for natural gas must be allocated from the total. The Natural Gas Annual (DOE 1995b) reports quantities of natural gas consumed as lease fuel but it does not indicate what percentage of this fuel should be attributed to the extraction of crude oil rather than the associated natural gas. According to DeLuchi (1993) a significant portion of the lease fuel is consumed in the repressuring of oil wells by natural gas reinjection, a fuel demand that should clearly be attributed to crude oil production. The lease fuel allocation was carried out following the methods used in DeLuchi (1993) updated using 1994 data from the Natural Gas Annual (DOE 1995b).

The U.S. Bureau of the Census, Census of Mineral Industries (DOC 1995a) has the most detailed data available for other energy use in the natural gas extraction industry. Again the data is reported for both crude petroleum and natural gas combined. The Census data has the added problem of a rather significant

**Table 7.3 Inputs and Outputs of the
Natural Gas Production Segment**

	<i>Inputs/Outputs per 10¹² Btu of natural gas produced</i>
Inputs	
1 natural gas	1,120,000 MBtu
2 electricity	1,020 MBtu
3 fuel oil 2/4	43,330 MBtu
Outputs	
<i>Products</i>	
4 natural gas	1 x 10 ¹² Btu
<i>Airborne Residuals</i>	
5 NO _x	190,000 lb
6 SO _x	17,300 lb
7 CO	37,200 lb
8 Pb	N.I.
9 PM ₁₀	N.I.
10 TSP	679 lb
11 CO ₂	9,670,000 lb
12 CH ₄	673,000 lb
13 NMVOCs	41,600 lb
14 N ₂ O	257 lb

* Includes onshore and offshore domestic gas production, associated gas production, and natural gas processing.

N.I.: Not Included

undistributed fuels category (fuels for which the type is not reported) which must be redistributed among the known fuels used. This is done based on the energy value of reported fuel consumption, by type. As with lease fuel, DeLuchi's method (1993) is used to allocate energy consumption between gas and oil.

The U.S. Bureau of the Census, Census of Mineral Industries (DOC 1995b) also includes energy use data for oil and gas field services. Oil and gas field services include drilling and well preparation operations almost exclusively. Because oil and gas well drilling and preparation are similar, fuel consumed in oil and gas field services is allocated between gas and oil based on drilling costs taken from EIA's Annual Energy Review (DOE 1995), which reports average cost per well for oil and gas wells.

Some electricity production occurs in gas and oil field production. The Census (DOC 1995a, b) reports the quantity of electricity generated and used in oil and gas extraction operations in 1992. According to AP-42 (EPA 1995) stationary dual-fuel engines have been used almost exclusively for prime electric power generation in gas and oil extraction operations. These dual-fuel engines run primarily on natural gas (95%) plus a small amount of diesel fuel to ignite the gas (5%). Electricity generated by gas-fired engines is allocated to natural gas production based on a back calculation from kilowatt-hours of generated electricity.

Emissions from fuel consumption in gas fields are estimated based on the above estimates of fuel consumption in conjunction with emissions factors primarily from the EPA. Emissions factors for well drilling equipment are taken from AP-42 (EPA 1995a) listed under "Emission Factors for Uncontrolled Gasoline and Diesel Industrial Engines" and "Gaseous Emissions for Large Uncontrolled Stationary Diesel and All Stationary Dual-Fuel Engines" (Tables 3.3.2 and 3.4.1). According to both AP-42 and the Oil and Gas Emissions Survey (EPA 1992), these emission factors apply to portable well-drilling equipment and large-bore well-drilling equipment.

All fuel excluding natural gas is assigned to well drilling activities. Most other machines used in gas field operations (including heaters, separators, and dehydrators) are fueled by natural gas. After subtracting diesel fuel use in large-bore stationary engines used to generate electricity, other fuel use is assigned to well drilling equipment. All gasoline use is assigned to portable well-drilling equipment and it is assumed that 50% of diesel fuel goes to portable and 50% to stationary well-drilling equipment. Emissions resulting from residual fuel oil and crude petroleum are considered negligible.

Other gas field activities include natural gas compression at the wellhead. The 1993 EPA Report to Congress (EPA 1993) assumes that compressors are used in the field when the natural gas extracted is of sufficient quality to be injected directly into the transmission system. The report estimates the quantity of lifted gas injected directly into the transmission system and uses an estimate of 72.7 million cubic feet (cf) of fuel per billion cf of gas produced to determine total fuel use. To obtain a fuel-use factor per scf of natural gas, total fuel used in field compressors is divided by marketed production (including natural gas and natural gas liquids). Both Radian (1996a) and EPA (1995a) report that only reciprocating engines are used in the field. According to AP-42 (EPA 1995a) reciprocating engines of 2-stroke design account for approximately 2/3 of installed capacity. A source from Radian estimates that lean burn engines account for the majority of reciprocating compressors. Hence the remaining 1/3 installed capacity is distributed among rich burn and lean burn 4-cycle engines according to a 75:25 ratio.

In addition, there are some emissions from heater treaters in natural gas field production. According to the Oil and Gas Field Emissions Survey (EPA 1992), the combustion of natural gas in an indirect fired

heater treaters used in the field will produce emissions similar to emissions for small, uncontrolled industrial boilers. All natural gas not consumed in field compressors is assigned to small, uncontrolled industrial boilers.

Finally, data from Radian (1996a) is used to estimate additional fugitive emissions of methane from natural gas field production operations. The combined inventory for natural gas field production is presented in Appendix D.2, Table D.2.15.

Scenario Information

Gas production is split between dedicated gas wells and co-producing oil wells based on data in EIA (1993b). According to this source 26% of domestic natural gas is from co-producing wells and the remaining 74% is from dedicated gas wells.

7.2.2 Natural Gas Processing

Processes Involved in Natural Gas Processing

After extraction and field treatment, the natural gas is transported to a processing plant where further removal of carbon dioxide, water, and hydrogen sulfide occurs to make the gas "pipeline quality." Hydrocarbon removal is achieved using compression, absorption, cryogenic, or adsorption processing. Desiccant dehydration techniques are used to remove water from the gas. Depending upon the raw gas quality and the end-use requirements, gas is often "sweetened" to remove additional quantities of hydrogen sulfide.

EVTECA Process Descriptions and Assumptions

As with natural gas field production, inventory data for gas processing activities used in this study is based on national average gas quality and processing activities. The primary data source for gas processing energy use and emissions was DOE (1983). Because of the age of this data, more recent literature was reviewed to check the DOE estimates. In several cases the DOE values were revised based on this literature review. The data sources for these estimates are described below.

Sulfur oxide emissions estimates for gas processing were developed from aggregate data for natural gas production from EPA (1995b). This data includes activities besides natural gas processing, however the major source of sulfur emissions in gas production is from the removal of sulfur in gas processing plants. Sulfur emissions per unit gas production are estimated by dividing 1994 emissions by marketed production of natural gas in 1994 (DOE 1995b).

Methane emissions are based on estimates of energy consumption in gas processing plants, and emissions factors for gas processing equipment, as well as fugitive methane emissions estimates. The primary data sources include Radian (1996a,b), and AP-42 emission factors for natural gas compressors. In addition, some natural gas is assumed to be consumed in boilers. Emissions of methane from this source are estimated using AP-42 emission factors for small, uncontrolled industrial boilers.

Particulate emissions are also estimated based on natural gas consumption estimates in gas processing plants. AP-42 emissions factors for compressors do not include estimates of particulate

emissions, and no factors are given for direct fired heaters. AP-42 emissions factors for small, uncontrolled industrial boilers are instead used to estimate particulate emissions for gas use not allocated to compressors and heaters.

VOC emissions were estimated from another Radian study (Radian 1995) on glycol dehydrator emissions, the major source of VOCs in the natural gas processing industry. Radian values are converted to emission per unit throughput for the sites included in the study, are then converted to annual emissions based on Radian estimates of total national dehydrator throughput, and finally are converted back to emissions per unit marketed gas production using Natural Gas Annual Data (DOE 1995b).

The complete gas processing inventory is presented in Appendix D.2, Table D.2.16.

7.2.3 Natural Gas Transmission

Processes Involved in Natural Gas Transmission

After processing, the gas is compressed to over 1000 psig (DOE 1983) and transmitted via pipeline to the power plant. Natural gas-fired internal combustion engines or gas turbines are most often used to power compressors for gas transmission, although some electricity is used directly for this purpose.

EVTECA Process Descriptions and Assumptions

Energy requirements for natural gas transmission are based on DOE (1983). These values are converted to values per ton mile of gas transported. Emissions for gas transportation are taken from DeLuchi (1991), and include methane emissions from pipeline leaks. The gas transportation inventory is presented in Appendix D.2, Table D.2.17. Total transportation requirements are modeled assuming 1,000 mile pipeline distance.

7.3 Uranium Extraction, Processing, Fuel Fabrication and Transportation

Processes Involved in Uranium Extraction, Processing, Fuel Fabrication, and Transportation

The utility dispatch scenarios for Washington, D.C. and Houston do not call for electricity from nuclear power plants, and hence the uranium fuel cycle is not used in the analysis for these two cities. Had the total-energy-cycle analysis been extended to Chicago, however, information on this fuel cycle would have been required. The description of the nuclear fuel cycle, and data developed for its characterization, are described below.

The uranium energy cycle is by far the most complex production cycle considered in this analysis, as it includes mining, milling, conversion, enrichment, and fuel fabrication activities that occur prior to delivery to the power plant. In 1985, 52% of all U_3O_8 (yellowcake) was produced in the U.S. from underground mines operating in the Southwestern U.S. (EIA 1993a), although recent data implies that open-pit mining operations have increased their share in the past few years.¹ Energy consumption at the mine is primarily associated with diesel fuel or electricity used in excavation equipment.

¹ Data on uranium operations are unusually variable, owing to the variability of the industry, stockpiling at the power plant, and information being withheld to avoid disclosure of company-specific data (EIA 1993a).

EVTECA Process Descriptions and Assumptions

There are two techniques for uranium extraction: open-pit mining and underground mining. Two tables in Appendix D.2 describe the inputs, outputs and emissions levels for the open-pit method (Table D.2.18) and underground mining (Table D.2.19) based on a national average practices (DOE 1983). After extraction, the ore is crushed and ground before being exposed to a leaching compound with acid or alkaline reagents that extract the uranium. Milling constitutes the next step, which produces yellowcake. Besides chemical inputs, these milling activities consume natural gas for process heat and electricity. Table D.2.20 in Appendix D.2 provides the inputs, outputs, and emissions for this step. After milling, the yellowcake is then conveyed to a conversion plant in Illinois or Oklahoma where the U_3O_8 is converted to uranium hexafluoride (UF_6). Table D.2.21 outlines the inputs, outputs and emissions for this process. The UF_6 is transported to a DOE enrichment facility (the two primary facilities are located in Ohio and Kentucky) where it is further enriched via a gaseous diffusion technique that uses a filter to separate out UF_6 laden with higher concentrations of U-235 (the fissionable form of uranium) than of U-238 (the more common isotope of uranium). The inputs, outputs, and emissions for this enrichment process are shown in Table D.2.22. The enriched UF_6 is then moved to one of five fuel fabrication facilities in the U.S. that convert the feedstock to uranium oxide (UO_2) in a form that can be used by the power plant. The inputs, outputs, and emissions for fuel fabrication are shown in Table D.2.23. The majority of the conversion and enrichment processes consume electricity and natural gas (for process heating) as well as various processing materials. Transportation of the uranium through the different steps of processing is done exclusively via truck. Although there are four different transportation legs involved in the uranium energy cycle, the total energy consumed in trucking the fuel and its derivatives is small relative to shipments of other fuels.² Table D.2.24 provides the amount of diesel energy consumed per ton of uranium transported, as well as the emissions factors for these vehicles.

Scenario Information

Transportation requirements for uranium are the same for each of the study cities for the legs uranium milling to conversion (1,000 miles), uranium conversion to enrichment (500 miles), and enrichment to fuel fabrication (800 miles).

7.4 Hydropower Production

On a national basis, electricity produced from water accounts for roughly 8% of the total power produced (EIA 1994), with shares being much higher in some regions (e.g., the Pacific Northwest). The energy cycle associated with hydropower is short, as the water is converted directly into power at the site of collection (i.e., reservoir or dam). Non-operation phase energy cycle components (e.g., constructing the dam) are more significant for this technology. No inputs and outputs of hydropower production were included in this analysis.

² In 1992, total deliveries of uranium were 11,700 short tons of U_3O_8 -equivalent material (EIA 1993a), while coal consumption in the utility sector was 779,800,000 short tons (EIA 1993b).

7.5 "Generic" Electricity Production

Many processes within the EVTECA use electricity as an input. For example, electricity is used in oil field production, oil pipelines, refineries, butane and methanol production, coal mining, uranium mining and processing, and battery and automobile materials manufacturing. These processes are located all over the United States, so it would have been inappropriate to apply emission factors for the utilities in the EVTECA metropolitan areas (Houston, DC, etc.,) to estimate residuals from electricity used in these processes. Therefore, emissions associated with the generation of "generic" electricity were estimated using M. Wang's GREET model. The GREET model (Wang 1996) provides estimates of average power plant emission factors for various power plant fuel types in operation in 2005. It also contains estimates of the average power plant generation mix (e.g., the percent coal-fired plants supply of total electricity) in that year. These assumptions were used to calculate national-average emission factors for use in miscellaneous processes. The inputs and outputs for generic electricity production are found in Table D.2.25 (Appendix D.2).

A special version of generic electricity production process was developed for the electricity input to aluminum production. This version, shown in Table D.2.26, is based on the power plant mix in the Pacific Northwest, where hydropower plays a larger role in producing electricity.

7.6 References for Chapter 7

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8.0 Processes Involved in Vehicle and Battery Manufacturing

This chapter discusses the processes involved in manufacturing conventional and electric vehicles, and electric vehicle batteries. These are shown with dotted lines in Figures 8.1 and 8.2. In addition to the energy consumed when vehicles are used for transportation, energy is also required to produce them. Energy is used to produce vehicle materials (e.g., iron, steel, and plastics) and in the vehicle assembly process. Additionally, environmental residuals are generated in the production of these materials and in vehicle assembly. Similarly, the production of EV batteries and the materials used to make them uses energy and generates emissions. Because the materials in the vehicle and batteries are available for recycling at the end of the vehicle or battery life-cycle and can displace virgin materials, some production energy can be recovered when vehicle and battery materials are recycled. Recycling processes are described below, but with a few exceptions, recycling was not explicitly considered in this assessment. A generalized schematic of the basic process steps involved in vehicle manufacturing is shown in Figure 8.3.

In this study, we focused on those processes that could have significant impacts on the total vehicle energy cycles from an energy and environmental perspective. Previous studies, as well as estimates made at the beginning of this study, suggested that energy and environmental impacts from material processing are considerably smaller than those from the use of the vehicle. (This is a typical finding when one compares the impacts of production versus use of durable goods.) Therefore, we chose to focus data collection efforts on the most significant materials. These include the materials which comprise the bulk of the vehicle mass and those which are unique to EVs (i.e., the battery materials). We also qualitatively reviewed minor materials for possible "red flags," i.e., potentially significant resource or environmental effects. Analysts interested in specific design aspects of EVs and CVs should characterize the materials in more detail.

This chapter is divided into three sections. Section 8.1 briefly discusses the material composition of the EVs and CVs included in the analysis. Section 8.2 describes production of the materials used in CV and EV shell manufacture. Section 8.3 describes production of materials used in the EV batteries. Flow charts describing the energy and materials flows for production and recycling of each material are provided (for most major processes), along with brief descriptions of the processes. Data on inputs and outputs for each materials-production process included in the study are contained in a standardized table format in Appendices D.2 and D.4. A summary that aggregates data for all processes involved in producing each major material in EVs, CVs, and EV batteries is contained in this chapter.

Emission factors associated with the processes were usually derived from the background reports (EPA, 1995) that support the U.S. Environmental Protection Agency's Compilation of Emission Factors (AP-42). If ranges were presented in the original source, the midpoint was used (unless noted). Data on energy and other inputs were derived from various sources. Emissions associated with fuel combustion were estimated using standard emission factors (i.e., the same emission factors were used for combustion within all processes.) Carbon dioxide emissions were calculated stoichiometrically.¹ Emissions of other airborne emissions from combustion were estimated using emission factors from AP-42 (EPA 1995) and the Tellus Institute (1992) (for oil combustion in boilers). The actual (national average) fuel mix within an industry was used when available; fuel oil 6/7 was assumed to be used as the combustion fuel when actual fuel consumption shares were not available. In cases where electricity is consumed by processes, it is assumed that the electricity is generated by a fuel mix representative of the U.S. national average. The one exception to this is aluminum production

¹ Representative molecular formulae for fuels were CH₄ for methane, CH₂ for oil, and CH for coal. Typical heats of combustion for methane, heavy distillate, and coal burned in industrial boilers were taken from the DOE Monthly Energy Review (DOE 1994).

which is more heavily weighted toward hydropower electricity generation. The fuel consumption and emissions from this "generic" electricity are discussed in Section 7.5. References for individual processes can be found in the tables contained in Appendix D.

Where several processes can provide the same product output, assumptions were made about the shares of product derived from each of the competing processes. In such cases, some sections below contain a subsection called "Scenario Information."

Figure 8.1 Segments in Electric Vehicle Energy Cycle Discussed in Chapter 8 (shown with dotted lines)

**Figure 8.2 Segments in Conventional Vehicle Energy Cycle Discussed in Chapter 8
(shown with dotted lines)**

8.1 Vehicle and Battery Composition

The material composition of CVs and EVs by model year and vehicle type are presented in Tables 8.1-8.6. The tables show material composition of the vehicle shell,² as well as the total weight of the shell. As indicated in these tables, just a few materials constitute a significant fraction of the mass of vehicle's shell. Approximately two-thirds of each CV and EV shell is iron and steel, and approximately 85% of each shell is iron, steel, aluminum, plastic and rubber. This is consistent with the average composition of U.S. passenger cars in 1994 as shown in Table 8.7. The tables show that we expect small changes in these percentages to occur over time, but we do not assume any major material substitutions. Nor does this analysis assume any

² Within the context of this report, the vehicle shell (also called simply "shell") for the CVs consists of the entire vehicle with all its parts, but for the EVs, it consists of the entire vehicle, excluding the battery.

preferential shifts in use of lighter materials in the EV shell. Additional detail regarding the derivation of the material composition of the CV and EV shells is contained in Appendix D.3.

Tables 8.4-8.6, which present EV composition data, also present the individual battery weight and lifetime battery weight of the EVs. The derivation of the individual battery weights is described in Appendix D.3. We assume that each Pb-acid battery will be replaced twice over the life of an EV and all other battery types will be replaced once. With these replacement assumptions, lifetime battery weight is derived. Lifetime battery weight is a measure of how much battery material must be manufactured and input into an EV during its lifetime.³ The material composition of the batteries is described in Section 8.3.

Table 8.1 Assumed Composition of Conventional Vehicles Built (Pre-2003) by Vehicle Type

Materials	Two-Seater		Compact		Mini-Minivan		Minivan		Full-Size Van	
	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total
Stainless Steel	25	1.27	37	1.42	35	1.45	50	1.40	63	1.42
Mild Steel	895	45.43	1150	44.15	1120	46.28	1690	47.21	2160	48.65
HS Steel	162	8.22	216	8.29	200	8.26	290	8.10	350	7.88
Other Steel	25	1.27	35	1.34	30	1.24	45	1.26	57	1.28
Cast Iron	245	12.44	335	12.86	300	12.40	425	11.87	550	12.39
Aluminum	110	5.58	150	5.76	130	5.37	185	5.17	230	5.18
Copper/Brass	25	1.27	35	1.34	30	1.24	45	1.26	55	1.24
Zinc Die Casting	10	0.51	12	0.46	10	0.41	20	0.56	25	0.56
Powder Metal	15	0.76	23	0.88	20	0.83	30	0.84	40	0.90
Plastic	150	7.61	200	7.68	180	7.44	270	7.54	330	7.43
Rubber	83	4.21	110	4.22	100	4.13	145	4.05	175	3.94
Glass	50	2.54	75	2.88	65	2.69	100	2.79	120	2.70
Lead	15	0.76	22	0.84	20	0.83	25	0.70	32	0.72
Fluids	110	5.58	140	5.37	130	5.37	180	5.03	143	3.22
Other	50	2.54	65	2.50	50	2.07	80	2.23	110	2.48
Subtotal	1970	100.00	2605	100.00	2420	100.00	3580	100.00	4440	100.00
Total	1970	100.00	2605	100.00	2420	100.00	3580	100.00	4440	100.00

³ This weight drives the energy consumption and environmental releases associated with manufacturing the batteries for each vehicle. In other parts of the study where vehicle performance is the focus, an individual battery module weight is used to estimate total vehicle weight while driving.

Table 8.2 Assumed Composition of Conventional Vehicles Built (2003-2007) by Vehicle Type

Materials	Two-Seater		Compact		Minivan		Full-Size Van	
	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total
Stainless Steel	25	1.27	37	1.42	50	1.40	63	1.42
Mild Steel	895	45.43	1150	44.15	1690	47.21	2160	48.65
HS Steel	162	8.22	216	8.29	290	8.10	350	7.88
Other Steel	25	1.27	35	1.34	45	1.26	57	1.28
Cast Iron	245	12.44	335	12.86	425	11.87	550	12.39
Aluminum	110	5.58	150	5.76	185	5.17	230	5.18
Copper/Brass	25	1.27	35	1.34	45	1.26	55	1.24
Zinc Die Casting	10	0.51	12	0.46	20	0.56	25	0.56
Powder Metal	15	0.76	23	0.88	30	0.84	40	0.90
Plastic	150	7.61	200	7.68	270	7.54	330	7.43
Rubber	83	4.21	110	4.22	145	4.05	175	3.94
Glass	50	2.54	75	2.88	100	2.79	120	2.70
Lead	15	0.76	22	0.84	25	0.70	32	0.72
Fluids	110	5.58	140	5.37	180	5.03	143	3.22
Other	50	2.54	65	2.50	80	2.23	110	2.48
Subtotal	1970	100.00	2605	100.00	3580	100.00	4440	100.00
Total	1970	100.00	2605	100.00	3580	100.00	4440	100.00

Table 8.3 Assumed Composition of Conventional Vehicles Built (2008-2010) by Vehicle Type

Materials	Two-Seater		Compact		Minivan		Full-Size Van	
	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total
Stainless Steel	25	1.27	37	1.42	50	1.40	63	1.42
Mild Steel	895	45.43	1080	42.93	1525	44.59	1955	46.04
HS Steel	162	8.22	216	8.29	290	8.10	350	7.88
Other Steel	25	1.27	35	1.34	45	1.26	57	1.28
Cast Iron	155	7.96	215	8.55	280	8.19	380	8.95
Aluminum	155	7.96	216	8.59	300	8.77	350	8.24
Copper/Brass	25	1.27	35	1.34	45	1.26	55	1.24
Zinc Die Casting	10	0.51	12	0.46	20	0.56	23	0.54
Powder Metal	15	0.76	23	0.88	30	0.84	38	0.89
Plastic	173	8.88	235	9.34	305	8.92	395	9.30
Rubber	83	4.21	110	4.22	145	4.05	175	3.94
Glass	50	2.54	75	2.88	100	2.79	120	2.70
Lead	15	0.76	22	0.84	25	0.70	32	0.72
Fluids	110	5.58	140	5.37	180	5.03	143	3.22
Other	50	2.54	65	2.50	80	2.23	110	2.48
Subtotal	1948	100.00	2516	100.00	3420	100.00	4246	100.00
Total	1948	100.00	2516	100.00	3420	100.00	4246	100.00

Table 8.4 Assumed Composition of Electric Vehicles Built (Pre-2003) by Vehicle Type

Materials	Two-Seater		Compact		Mini-Minivan		Minivan		Full-Size Van	
	PbA		PbA		NaS		NiCd		PbA	
	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total
Stainless Steel	20	0.49	25	0.51	20	0.59	35	0.77	35	0.44
Mild Steel	890	21.72	1140	23.25	1100	32.70	1660	36.49	2050	25.57
HS Steel	125	3.05	160	3.26	150	4.46	230	5.06	270	3.37
Magnet Steel	47	1.15	60	1.22	55	1.63	80	1.76	85	1.06
Other Steel	10	0.24	13	0.27	10	0.30	20	0.44	30	0.37
Cast Iron	140	3.42	180	3.67	160	4.76	220	4.84	250	3.12
Aluminum	90	2.20	110	2.24	100	2.97	150	3.30	180	2.25
Copper/Brass	53	1.29	65	1.33	60	1.78	90	1.98	100	1.25
Zinc Die Casting	10	0.24	13	0.27	10	0.30	16	0.35	20	0.25
Powder Metal	10	0.24	13	0.27	10	0.30	15	0.33	20	0.25
Plastic	167	4.08	210	4.28	200	5.95	285	6.27	330	4.12
Rubber	85	2.07	110	2.24	100	2.97	150	3.30	175	2.18
Glass	60	1.46	75	1.53	65	1.93	100	2.20	120	1.50
Fluids	25	0.61	30	0.61	30	0.89	50	1.10	60	0.75
Other	50	1.22	65	1.33	60	1.78	90	1.98	110	1.37
Subtotal	1782	43.48	2269	46.28	2130	63.32	3191	70.15	3835	47.84
Vehicle Battery	772		878		617		679		1394	
Lifetime Batteries	2316	56.52	2634	53.72	1234	36.68	1358	29.85	4182	52.16
Total	4098	100.00	4903	100.00	3364	100.00	4549	100.00	8017	100.00

Table 8.5 Assumed Composition of Electric Vehicles Built (2003-2007) by Vehicle Type

Materials	Mini-Compact		Compact						Minivan						Full-Size Van					
	PbA		NaS		NiCd		NiMh		NaS		NiCd		NiMh		NaS		NiCd		NiMh	
	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total
Stainless Steel	20	0.40	25	0.61	25	0.46	25	0.58	35	0.70	35	0.60	35	0.70	35	0.50	35	0.43	35	0.52
Mild Steel	890	18.00	1140	27.99	1140	21.09	1140	26.53	1660	33.01	1660	28.35	1660	33.35	2050	29.52	2050	25.13	2050	30.45
HS Steel	125	2.53	160	3.93	160	2.96	160	3.72	230	4.57	230	3.93	230	4.62	270	3.89	270	3.31	270	4.01
Magnet Steel	47	0.95	60	1.47	60	1.11	60	1.40	80	1.59	80	1.37	80	1.61	85	1.22	85	1.04	85	1.26
Other Steel	10	0.20	13	0.32	13	0.24	13	0.30	20	0.40	20	0.34	20	0.40	30	0.43	30	0.37	30	0.45
Cast Iron	140	2.83	180	4.42	180	3.33	180	4.19	220	4.37	220	3.76	220	4.42	250	3.60	250	3.06	250	3.71
Aluminum	90	1.82	110	2.70	110	2.04	110	2.56	150	2.98	150	2.56	150	3.01	180	2.59	180	2.21	180	2.67
Copper/Brass	53	1.07	65	1.60	65	1.20	65	1.51	90	1.79	90	1.54	90	1.81	100	1.44	100	1.23	100	1.49
Zinc Die Casting	10	0.20	13	0.32	13	0.24	13	0.30	16	0.32	16	0.27	16	0.32	20	0.29	20	0.25	20	0.30
Powder Metal	10	0.20	13	0.32	13	0.24	13	0.30	15	0.30	15	0.26	15	0.30	20	0.29	20	0.25	20	0.30
Plastic	167	3.38	210	5.16	210	3.89	210	4.89	285	5.67	285	4.87	285	5.73	330	4.75	330	4.05	330	4.90
Rubber	85	1.72	110	2.70	110	2.04	110	2.56	150	2.98	150	2.56	150	3.01	175	2.52	175	2.15	175	2.60
Glass	60	1.21	75	1.84	75	1.39	75	1.75	100	1.99	100	1.71	100	2.01	120	1.73	120	1.47	120	1.78
Fluids	25	0.51	30	0.74	30	0.56	30	0.70	50	0.99	50	0.85	50	1.00	60	0.86	60	0.74	60	0.89
Other	50	1.01	65	1.60	65	1.20	65	1.51	90	1.79	90	1.54	90	1.81	110	1.58	110	1.35	110	1.63
Subtotal	1782	36.04	2269	55.71	2269	41.98	2269	52.80	3191	63.45	3191	54.50	3191	64.11	3835	55.22	3835	47.01	3835	56.96
Vehicle Battery	1054		902		1568		1014		919		1332		893		1555		2161		1449	
Lifetime Batteries	3162	63.96	1804	44.29	3136	58.02	2028	47.20	1838	36.55	2664	45.50	1786	35.89	3110	44.78	4322	52.99	2898	43.04
Total	4944	100.00	4073	100.00	5405	100.00	4297	100.00	5029	100.00	5855	100.00	4977	100.00	6945	100.00	8157	100.00	6733	100.00

Table 8.6 Assumed Composition of Electric Vehicles Built (2008-2010) by Vehicle Type

Materials	Mini-Compact		Compact						Minivan						Full-Size Van					
	PbA		NaS		NiCd		NiMh		NaS		NiCd		NiMh		NaS		NiCd		NiMh	
	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total	Mass, kg	% of Total
Stainless Steel	20	0.45	25	0.66	25	0.52	25	0.64	35	0.75	35	0.66	35	0.77	35	0.55	35	0.48	35	0.57
Mild Steel	840	19.00	1070	28.26	1070	22.05	1070	27.25	1500	32.24	1500	28.38	1500	32.95	1850	28.96	1850	25.34	1850	30.25
HS Steel	125	2.83	160	4.23	160	3.30	160	4.08	225	4.84	225	4.26	225	4.94	265	4.15	265	3.63	265	4.33
Magnet Steel	47	1.06	60	1.58	60	1.24	60	1.53	80	1.72	80	1.51	80	1.76	85	1.33	85	1.16	85	1.39
Other Steel	10	0.23	13	0.34	13	0.27	13	0.33	20	0.43	20	0.38	20	0.44	30	0.47	30	0.41	30	0.49
Cast Iron	50	1.13	60	1.58	60	1.24	60	1.53	75	1.61	75	1.42	75	1.65	80	1.25	80	1.10	80	1.31
Aluminum	135	3.05	176	4.65	176	3.63	176	4.48	265	5.70	265	5.01	265	5.82	300	4.70	300	4.11	300	4.91
Copper/Brass	53	1.20	65	1.72	65	1.34	65	1.66	90	1.93	90	1.70	90	1.98	100	1.57	100	1.37	100	1.64
Zinc Die Casting	10	0.23	13	0.34	13	0.27	13	0.33	16	0.34	16	0.30	16	0.35	20	0.31	20	0.27	20	0.33
Powder Metal	10	0.23	13	0.34	13	0.27	13	0.33	15	0.32	15	0.28	15	0.33	20	0.31	20	0.27	20	0.33
Plastic	190	4.30	245	6.47	245	5.05	245	6.24	320	6.88	320	6.05	320	7.03	395	6.18	395	5.41	395	6.46
Rubber	85	1.92	110	2.91	110	2.27	110	2.80	150	3.22	150	2.84	150	3.29	175	2.74	175	2.40	175	2.86
Glass	60	1.36	75	1.98	75	1.55	75	1.91	100	2.15	100	1.89	100	2.20	120	1.88	120	1.64	120	1.96
Fluids	25	0.57	30	0.79	30	0.62	30	0.76	50	1.07	50	0.95	50	1.10	60	0.94	60	0.82	60	0.98
Other	50	1.13	65	1.72	65	1.34	65	1.66	90	1.93	90	1.70	90	1.98	110	1.72	110	1.51	110	1.80
Subtotal	1710	38.67	2180	57.58	2180	44.93	2180	55.53	3031	65.14	3031	57.35	3031	66.57	3645	57.05	3645	49.92	3645	59.61
Vehicle Battery	904		803		1336		873		811		1127		761		1372		1828		1235	
Lifetime Batteries	2712	61.33	1606	42.42	2672	55.07	1746	44.47	1622	34.86	2254	42.65	1522	33.43	2744	42.95	3656	50.08	2470	40.39
Total	4422	100.00	3786	100.00	4852	100.00	3926	100.00	4653	100.00	5285	100.00	4553	100.00	6389	100.00	7301	100.00	6115	100.00

Table 8.7 Estimated Average Material Content in U.S.-Built Passenger Cars (1994)

MATERIAL	MASS (kg)	PERCENTAGE (%)
Stainless Steel	20.0	1.4
Mild Steel	631.0	43.8
High-Strength Steel	120.0	8.3
Other Steel	19.0	1.4
TOTAL STEEL	790.0	54.9
Cast Iron	185.0	12.8
TOTAL FERROUS	975.0	67.7
Aluminum	83.0	5.8
Copper	19.0	1.3
Zinc Die Castings	7.0	0.5
Powder Metal	12.0	0.8
Plastics/Composites	112.0	7.7
Rubber	61.0	4.2
Glass	40.0	2.7
Fluids/Lubricants	86.0	5.9
Other Materials	45.0	3.1
TOTAL	1,440.0	100.0

Source: American Automobile Manufacturers Association, Motor Vehicle Facts and Figures, 1994.

8.2 Vehicle Materials

Vehicle manufacture is a complex process that involves the production of many components from a substantial number of materials. This section is divided into three sub-sections that describe the major types of materials and components used in vehicles: metals, plastics, and other miscellaneous materials. Although the assembly of vehicle components to produce complete vehicles also uses energy and creates some environmental burden, we did not include an analysis of vehicle assembly in this study because the effects are estimated to be similar between CVs and EVs, so in this comparative analysis of EVs versus CVs, including the vehicle assembly would not change the relative environmental or energy results.

As shown in the material composition tables (8.1 - 8.6), both EVs and CVs have been broken down into 15 basic material categories. Table 8.8 provides for an overall summary of the environmental and energy

inputs/outputs for each of these material categories. This data was used to generate the final TEC inventory. The data presented in Table 8.8 represent a summation of the inputs and outputs for all upstream processes involved in producing the material that were included in the EVTECA. In some cases, we included many upstream processes and in others, we included few or none. For instance, for steel we included coking, sintering, pig production, basic oxygen process, sheet making and steel parts stamping. Values in Table 8.8 show aggregated inputs and outputs for all of these processes (details on each process are included in Appendix D.4). Plastics production, on the other hand, involves use of chemical precursors, all of which could not be characterized for this analysis. Therefore, all processes upstream were not included, and the values in Table 8.8 represent a partial characterization of the inputs/outputs of the plastics-production process. (Note that lead is primarily a battery material and is discussed in Section 8.3.)

Table 8.8 Summary of Air Pollutant Emission Outputs of Major Materials Used in EV and CV Shells*

Airborne Emissions (lb/1000 tons)								
Material	NO _x	SO _x	CO	Pb	TSP	CO ₂	CH ₄	NMVOC
Steel Parts**	390	14200	1.89E+05	0.028	814	6.72E+06	710	288
Iron Castings	22500	38800	662	16	3730	9.29E+06	35.1	114
Aluminum Parts***	18200	7.11E+04	1820	0.594	6.31E+04	8.08E+06	183	286
Copper/Brass	19900	8.40E+05	11200	201	92400	8.12E+06	210	2470
Plastics	8200	45000	1300	NC	4000	7.82E+06	290	490
Styrene Butylene Rubber	23000	80400	3710	0.3	10200	1.99E+06	709	12600
Float Glass	11100	14100	490	0	2500	2.10E+06	45	400
Fiberglass	25400	25600	3100	0	1200	1.70E+06	37	35
Lead	5080	16900	245	238	1110	2.28E+06	29.8	52

* Zinc and powder metal were not characterized. No emissions of PM₁₀ or N₂O were included.

** The same characterization was used for stainless, mild, HS, and other steel.

*** Includes a mix of cast and wrought aluminum.

NC: Not Characterized

8.2.1 Metals

This section provides information regarding the processes associated with the production of: (1) steel, (2) cast iron, (3) aluminum, (4) copper, and (5) other metals. (Some information on recycling is also included.) Unit processes for production and fabrication of iron and steel, aluminum, and copper were analyzed in an earlier series of Argonne reports prepared for the U.S. Department of Energy, Office of Industrial Programs (Shen 1981; Arons and Wolsky 1978; Sparrow 1983; Darby and Arons 1979; Gaines 1980). Those reports contain detailed process descriptions and should be consulted for more explanation of the assumptions used here. Figure 8.4 shows a generalized schematic of the basic process steps involved in metal parts production. Each section below (on a specific metal) includes a brief description of the processes used to produce the metal, and, for major metals, corresponding process flow charts specific to those processes. Important assumptions made in estimating the inputs and outputs of individual processes are documented. Each section below contains a general description of the processes involved in producing the material, a section on the specific processes and assumptions used in the EVTECA, and if competing processes produce the product, a section called "Scenario Information" that describes the mix of processes used in this assessment.

8.2.1.1 Steel

Various types of steel comprised about 55% of the average U.S. passenger car in 1994 (see Table 8.7). For this analysis, no distinction was made between the various types of steel. Although variations exist in the inputs/outputs and exact process steps used to produce each type of steel, these differences did not appear to warrant a detailed analysis. One generic set of processes, as described in the sections below, was used for all steel parts in vehicles in the EVTECA.

Processes Involved in Steel Making

Steel is a major component of automobiles. The major processes involved in the method for producing "virgin" steel parts for automobiles (shown in Figure 8.5) include:

- iron ore production (mining)
- coking (i.e., producing coke from coal), pelletizing iron ore (producing iron ore pellets), and sintering (producing sinter from ore, cinder and scale), all of which produce inputs to the blast furnace
- pig iron production (using the blast furnace)
- raw steel production via the Basic Oxygen Process (BOP)
- the casting, rolling, and annealing of raw steel (the steel sheet production process)
- auto part stamping (the stamping of automobile parts out of sheet metal)

Recycling of steel auto parts can provide an alternative to production of virgin steel. In current practice, auto sheet is recycled into the general body of steel going to all uses; in the future, it is possible that auto sheet could be recycled back to new auto sheet. During the course of conducting this EVTECA, we characterized a recycled steel process. Recycled steel (which could theoretically be made into steel sheet and then stamped into parts) can be produced from scrap using the Electric Arc Furnace (EAF), sometimes known

as the minimill. This is also shown in Figure 8.5. However, we do not include this process in the EVTECA analysis because, currently, no steel in automobiles comes from minimills.

Primary (virgin) iron and steel production (i.e., the production of steel from raw iron ore using a blast furnace and Basic Oxygen Process) in the U.S. is concentrated in a band from Pennsylvania to Illinois, near several major population centers. Secondary production, or production from scrap using the EAF, is more widely distributed, with minimills in all parts of the country.

EVTECA Process Descriptions and Assumptions

The EVTECA focused on the most energy-intensive processes involved in production of steel auto parts. Not every process shown in Figure 8.5 was fully characterized (by quantifying inputs and outputs of the process) for inclusion in the EVTECA. Those that were characterized for the virgin steel parts production process, shown shaded in the figure, include coking, sintering, pig iron production (via Blast Furnace), raw steel production (BOP), steel sheet production, and steel parts stamping. We also characterized the recycled steel production (EAF), but as discussed above, it was not included in the final calculations. Each of these processes and the major assumptions used to characterize them are discussed below.

- **Coking.** Coking involves transforming coal into a relatively involatile, carbonaceous product called coke, which is a principal input to blast furnaces that produce pig iron. The production of coke for blast furnaces is a major source of emissions of both gases and particulates. Figure 8.6 shows the coke production and blast furnace parts segments of the iron and steel production process. The resulting particulates include carbon and benzene-soluble organics. Coal dust may be released during oven charging. Particulates that result from the steel-making process can be captured in hoods or other systems and sent to a baghouse, or for some operations, suppressed. Uncontrolled particulate emissions are on the order of 70 kg/tonne (140 lb/ton) of steel. Control efficiencies range from 91-99%. Gases include methane and carbon monoxide, the main constituents of coke oven gas, hydrogen, and other hydrocarbons. Sulfur dioxide emissions depend on the sulfur content of the coal feed and the underfire gas. Coke oven emissions are listed as hazardous air pollutants under Section 112 of the Clean Air Act. Benzene and other toxic volatile organic compound (VOC) emissions from the byproduct chemical plant have been a particular concern. Emissions vary from plant to plant and depend on operating conditions. Typical inputs and outputs, including emissions of particulates, SO₂, CO, VOCs, NO_x, and other pollutants from coke manufacturing operations are shown in Table D.4.1 (in Appendix D.4). Total energy consumption was disaggregated by fuel type using national-average shares of energy use in coke-oven underfiring (see Table 8.9 for the national values used). Large quantities of byproduct gases are used in coking.
- **Sintering.** Sintering involves processing iron ore, cinder, and scale into an intermediate product, sinter, which is input to the blast furnace (see Figure 8.6). Although sintering produces residuals from both fuel combustion and the sintering process itself (iron oxides, sulfur oxides, carbonaceous compounds and chlorides), data were not readily available. Only particulate emissions to the air have been quantified in this analysis (see Table D.4.2).

Table 8.9 Direct Use of Energy in the Steel Industry by Process Area for 1992

Fuel	Coke Production	Blast Furnaces	Coke-Oven Underfiring	Steel-Making Furnaces	Heating and Annealing	Other Uses ^a	Total
Coal (10 ³ tons)	26,520	-	-	-	-	1,411	27,931
Fuel Oil (10 ³ gal)	-	209,475	-	95	7,364	72,823	289,757
Natural Gas(10 ³ ft ³) ^b	-	77,676	319	20,754	169,481	74,722	342,952
Coke Oven Gas (10 ⁶ ft ³) ^c	-	15,237	129,518	1,440	77,518	86,378	310,091
Blast Furnace Gas (10 ⁶ ft ³) ^d	-	852,032	14,413	-	9,435	1,223,052	2,038,982
Electricity (10 ⁶ kWh)							
Generated	-	-	-	-	-	-	6,346
Purchased	-	-	-	-	-	-	36,470
Total	-	-	-	-	-	-	42,816

^a Includes boilers and heating.

^b 1,000 Btu/ft³.

^c 500 Btu/ft³.

^d 95 Btu/ft³.

Source: AISI (1993)

- Pig Iron Production via a Blast Furnace.** A major step in the iron- and steel-making process is the reduction of iron ore to pig iron in a blast furnace. This process is also illustrated in Figure 8.6. Coke, pellets, and sinter are the raw material for this process. Inputs and outputs, including emissions associated with the reduction of ore in the blast furnace are shown in Table D.4.3. In the future, the production process for pig iron may change to direct reduction, decreasing energy use for primary steel production and significantly decreasing air emissions by avoiding the current coking processes; however, this potential change was not included in this analysis.
- Steel Production via the Basic Oxygen Process (BOP).** The conversion of pig iron to raw steel is accomplished via the basic oxygen process. Figure 8.7 shows that the inputs to this process are pig iron, lime, scrap, alloying elements and refractories, and energy. Flat-rolled steel products from the BOP, including sheet for automobiles, typically contain about 25% scrap, mostly from sources inside the steel mill or from industrial sources. Inputs and outputs, including emissions resulting from the basic oxygen process are shown in Table D.4.4. The CO emissions are assumed to be uncontrolled. In the future, the production process for pig iron may change to direct reduction, decreasing the energy use for primary steel production and significantly decreasing air emissions by avoiding the current

coking processes. Although this could have impacts on the EVTECA results, estimation of the potential for this shift was considered beyond the scope of this study.

- **Steel Production via the Electric Arc Process.** An alternative to the primary steel production process described above (mining raw iron ore and processing it to make steel) is production of steel from scrap via the electric-arc furnace (EAF), as illustrated in Figure 8.8. Products from the EAF generally include structural shapes, reinforcing bar, wire, and nails, and contain virtually 100% scrap from a mix of pre- and post-consumer sources. Electric-arc furnaces processed 63% of the U.S. steel scrap consumed in 1990 (1990 Minerals Yearbook). Although no EAF actually produces auto sheet, some EAFs produce appliance sheet. There is some uncertainty about whether the EAF can ever economically produce sheet of high enough quality for automobiles. Inputs and outputs, including emissions from the EAF are shown in Table D.4.5.
- **Steel Sheet-Making.** This multi-step process involves the casting, reheating, pickling, rolling, and annealing of the steel, as can be seen in Figure 8.9. The process produces a considerable amount of home scrap which can be re-input to the process. Inputs, outputs, and emissions for the steel sheet production process are shown in Table D.4.6.
- **Steel Parts Production (Stamping).** Steel sheet is made into auto parts such as body panels by "stamping" by multiple dies. This process, fueled by electricity, is not particularly energy-intensive, but produces considerable scrap which must then be remelted and refabricated. Therefore, such offal must be minimized to reduce energy use. Figure 8.10 shows this process, and the values for inputs and outputs for a typical steel parts stamping operation are provided in Table D.4.7.

Scenario Information

In this EVTECA, we assume steel auto parts are produced via the virgin (primary) iron and steel production processes. This assumption is derived from the fact that currently, by mass, essentially all steel used in cars is produced via the BOP.

8.2.1.2 Cast Iron

Cast iron accounted for almost 13% of the average material content of U.S.-built passenger cars in 1994 (Table 8.7). It is expected to account for 8-12% of the average material content of the CV fleet, and 2-8% of the average content of EVs, in 2010.

Processes Involved in Production of Cast Iron Parts

Cast iron parts for automobiles are generally produced by automakers in their own foundries, using scrap iron and steel and some virgin pig iron as the raw material. Therefore, the processes involved in producing cast iron parts include:

- the processes involved in producing pig iron (i.e., iron ore mining, coking, pelletizing, sintering, and pig iron production via the blast furnace), as well as the recycling of scrap

- collecting and processing scrap iron and steel⁴
- charging (the melting of scrap, sometimes with pig iron added, in a cupola furnace, which resembles a small blast furnace) and casting the molten iron into shapes

EVTECA Process Descriptions and Assumptions

The processes involved in pig iron production are described in Section 8.2.1.1 above.

The inputs and outputs of the processing, charging and casting steps in the iron casting process are shown in Table D.4.8 in Appendix D. Foundry coke, similar to metallurgical coke but slightly more energy-intensive, supplies the heat to melt the metal, which is then poured into molds. Excess CO is burned off in an afterburner. The total energy required for gray iron castings is about 32×10^6 Btu/ton, mostly in the form of coal for coke production (see discussion above of coking). Note that offal (waste) rates affect the energy use for cast parts significantly, because rejected material must be melted again. Therefore, techniques like near-net-shape casting can significantly decrease energy use per part shipped.

In this assessment, 87% of the metal input into the iron casting process is assumed to be scrap iron and steel. The remaining 13% is assumed to be virgin pig iron (F. Stodolsky et al., 1995).

8.2.1.3 Aluminum

Aluminum comprised almost 6% of the average U.S.-built passenger car in 1994. In fact, transportation is the second largest U.S. market for aluminum, accounting for 16.5% of total aluminum sold (behind containers and packaging, at 29.1%). The quantity sold is considerably more than the quantity of final products estimated to be generated as waste, mainly because a large amount of scrap is produced during fabrication. Aluminum content of vehicles is expected to increase over time (see Tables 8.2 through 8.6).

Processes Involved in Aluminum Parts Production

Two types of aluminum are considered in this analysis -- cast and wrought aluminum. Wrought aluminum can be in the form of sheets (stamped parts) or extrusions. Most wrought aluminum produced today is "virgin" aluminum, produced by processing aluminum in bauxite ore via a series of energy-intensive process steps. Because it is so energy intensive, aluminum is heavily recycled today and is expected to be in the future. Aluminum castings are produced mostly from recycled material. Some recycled wrought parts are likely to be produced in the future. About 80% of the aluminum used in cars today is recovered from scrap (Bureau of Mines 1993).

Figures 8.11 and 8.12 show basic diagrams of the processes we expect to be involved in the future in wrought and cast-aluminum parts production. The virgin aluminum-making process starts with three major process steps:

- mining of bauxite ore (Bauxite Extraction)
- refining ore into alumina in what is known as the Bayer process (Alumina Production)

⁴ Scrap is reduced in size by shredding, shearing, cutting, or crushing, depending on the source.

- converting alumina into aluminum ingot through the Hall-Heroult process (Aluminum Ingot Production)

These steps result in the production of aluminum ingots, which can then be further processed into auto parts. To produce wrought parts, ingots undergo the following processing steps:

- melting of ingots to shapes (Aluminum Castings Production)
- fabrication of aluminum mill products (sheets)
- aluminum parts stamping.

To produce cast parts from virgin material, the following processes are used:

- mining of bauxite ore
- alumina production
- aluminum ingot production
- aluminum castings production

More commonly, cast parts are made from recycled aluminum (in Appendix D, this process is called Recycled Aluminum Castings Production. Theoretically, wrought parts could also be produced via aluminum casting using recycled aluminum as input, which would involve a melting process to produce ingots followed by fabrication of mill products and stamping.

EVTECA Process Descriptions and Assumptions

Figure 8.13 shows more detail for the first three steps of virgin aluminum production (ingot production), and Figure 8.14 shows the production of wrought aluminum parts from ingots. The alternative, recycling process is shown in Figure 8.15. Total energy for virgin production is about 199×10^6 Btu/ton and for recycled products is about 45×10^6 Btu/ton. The large difference between virgin and recycled aluminum production energy is due to the high energy requirement for reduction of alumina (Al_2O_3) to elemental aluminum metal. Most of the energy for both processes is in the form of electricity produced from both fuel combustion and hydroelectric power. Total energy purchases by the aluminum industry for 1989 are shown by process step in Table 8.10. (Note: the energy for recycling was estimated assuming no metal loss in the recycling loop. Because fabrication scrap must be processed again, raising the energy required to produce a final product, the total energy embodied in aluminum products is higher than indicated in this table.)

Tables showing EVTECA inputs and outputs of each major process step are included in Appendix D.4. These processes are described briefly as follows:

- **Bauxite Extraction.** The first stage of the aluminum-making process typically involves mining of the ore (using blasting), some basic processing steps to facilitate handling and refining, and transportation of the ore to the refining plant. Table D.4.9 in Appendix D shows inputs and outputs of this step.

Table 8.10 Sources and Uses of Energy by the Aluminum Industry for 1989 (Full Year) ^{a,b}

	Aluminum							
Production of Material and Sources of Energy	Bauxite Mining	Alumina Refining	Melting Metal	Holding, Melting, and Casting	Fabricating Mill Products	Other Fabrication	Total	Distribution (%)
Production (10 ⁶ lb)	-	10,031	8,885	25,879	17,133	727	-	-
Energy Form (10 ⁹ Btu):								
Natural Gas Products								
Natural Gas	-	47,077	13,632	53,704	51,159	2,809	168,381	20.7
Propane and LPG	-	-	134	588	697	83	1,501	0.2
Petroleum Products								
Distillate Oil	-	122	376	826	500	59	1,882	0.2
Residual Oil	-	-	33	625	19	-	677	0.1
Lube Oil	-	20	64	77	3,230	26	3,416	0.4
Gasoline/Kerosine	-	32	86	136	409	4	667	0.1
Petroleum Coke	-	51,785	-	-	-	-	51,785	6.4
Electricity								
Hydro	-	-	94,262	1,075	3,307	2,024	100,668	12.4
Thermal Purchased	-	2,383	302,139	8,051	57,890	1,823	372,285	45.8
Thermal Generated	-	8,380	77,470	530	3,537	-	89,916	11.1
Other								
Pitch	-	-	16,052	-	-	-	16,052	2.0
Coal and Miscellaneous	-	1,957	1,144	98	3,002	-	6,484	0.8
TOTAL ENERGY (10⁹ Btu)		59,971	557,176	65,992	123,748	6,827	813,713	100.0
ENERGY DISTRIBUTION		7.4	68.5	8.1	15.2	0.8	100.0	
Btu/lb		5,978	62,710	2,550	7,223	9,389		

a Detail may not add to totals due to rounding.

b Excludes energy embodied in material inputs and energy from processing abroad.

Source: Aluminum Association (1991)

- **Alumina Production (Bayer Process).** The refining process that converts the bauxite ore to alumina uses lime and caustic soda as inputs and is referred to as the Bayer Process. Large quantities of particulates are generated during bauxite grinding, calcining, and handling, these are generally recovered due to their large economic value, leaving small residual emissions. (See Table D.4.10)
- **Aluminum Ingot Production (Hall-Heroult Process).** This process converts alumina to aluminum ingots and uses an electrolyte composed of cryolite, aluminum fluoride, and fluorospar, and therefore produces emissions that include fluorides. Emissions from the aluminum reduction process, provided in Table D.4.11 include gaseous hydrogen fluoride, alumina, carbon monoxide, VOCs, and sulfur dioxide. Particulates include alumina, carbon, and aluminum and calcium fluorides. Additional VOCs are emitted from the anode baking process. Wet scrubbers and electrostatic precipitators may be used to control fluoride emissions, but fluoride adsorption systems are becoming prevalent. These control 99% of gaseous and particulate fluorides.
- **Virgin Aluminum Castings Production (Aluminum Melt and Cast).** After the alumina is converted into aluminum ingots, the ingots are melted and cast into shapes. See Table D.4.12.
- **Fabrication of Aluminum Mill Products.** These shapes are then subject to mill operations where they are converted into aluminum sheets and then sent to a parts stamping process. See Table D.4.13.
- **Aluminum Parts Stamping.** Mill products are stamped into parts that can be directly input into the automobile. See Table D.4.14. Note that this process is characterized to be the same as steel parts stamping.
- **Recycled Aluminum Castings Production.** The process of making cast aluminum parts involves preparing the scrap, melting it, and forming it into ingots with controlled composition, and then remelting the ingots and casting them into shapes for parts. This process is shown in Table D.4.15 (and in Figure 8.15). Aluminum scrap is melted in large gas-fired reverberatory furnaces, and magnesium is removed using chlorine or fluxes, leading to chloride emissions requiring controls. Alloy compatibility is a major concern for producing good quality parts from recycled materials. In current practice, the smaller quantities of wrought aluminum auto parts are recycled into the larger mass of castings, and undesirable elements are diluted. However, if the quantity of wrought auto parts rises significantly, dilution may become impractical and segregation of parts during recycling would become desirable.
- **Recycled Wrought Aluminum Ingot Production.** Although this is not currently a common practice, recycled wrought aluminum could be remelted, rolled and stamped to produce wrought aluminum parts. The first step would be ingot production; estimates of the energy and residuals that might result from this process are found in Table D.4.16. This would be followed by the fabrication of mill products and the aluminum parts stamping process described above. This chain of recycled wrought aluminum production steps was not included in the EVTECA. Sensitivity runs may be done in the future to assess the impact of increased use of recycled parts.

Scenario Information

To conduct the EVTECA, assumptions had to be made about: (1) the amount of wrought versus cast aluminum parts that will be used in vehicles in the future, and (2) the amount of virgin versus recycled aluminum that will be used.

- **Cast versus wrought parts.** The baseline 2000 and 2010 vehicle is projected to use three times as much aluminum in castings as in wrought parts (University of Michigan, 1992), although future growth could be concentrated in extruded space frames and rolled sheet body panels. For this assessment, we assumed vehicles would be produced using 75% cast aluminum and 25% wrought aluminum parts.
- **Recycled versus virgin aluminum production.** All wrought (sheet and extruded) aluminum currently used in automobile production is assumed to be virgin material (processing of which, of course, includes some internal recycling loops). Wrought products are assumed to go through the sequence: bauxite mining, Bayer and Hall-Heroult processes, aluminum melt and cast, fabrication of mill products and aluminum part stamping. In the future, some wrought aluminum parts may come from recycled aluminum, but this was not assessed in the EVTECA.

Cast aluminum products are largely made from recycled material now and are expected to be more so in the future. In our scenarios, we assumed 75% of cast aluminum parts will originate from the recycling process ("Recycled Aluminum Casting"), with the remainder produced via the virgin process (bauxite mining, Bayer and Hall-Heroult processes, and Aluminum Castings Production).

8.2.1.4 Copper

Pure copper's outstanding electrical conductivity makes it the material of choice for essentially all automotive wiring, including electric motors, although aluminum can be used if increased volume is acceptable. The other major automotive use of copper is the use of brass alloys (copper-zinc) in radiators. Copper accounted for only about 1% of the total mass of the average automobile in 1994 (see Table 8.7 above). Use in EVs will be greater (approximately 3% of the EV shell) because of its use in motors and carburetors. Still, because of the low mass in both CV's and EV's, this metal was examined in less detail than those discussed above.

Processes Involved in Copper Production

Copper production involves copper sulfide ore mining, concentration, pyrometallurgical processing, and production of copper wire or other products. Producing copper from ore is a very energy intensive process. The recycling process is considerably less energy-intensive, and also causes no sulfur emissions.⁵

EVTECA Process Descriptions and Assumptions

Copper is smelted or recovered by leaching from dilute sulfide ores found in the U.S. Southwest. The smelting process leads to significant emissions of sulfur oxides, which are captured and converted to sulfuric acid for sale. Residual emissions depend on the design of the plant and the pollution control technology in place. Because the ores are dilute, energy use in mining and beneficiation is significant. Total energy use is about 125×10^6 Btu/ton of fabricated product (Gaines 1980).

⁵ Energy requirements for copper recycling vary from about 6×10^6 Btu/ton for the highest grades that need only be remelted to as much as 42×10^6 Btu/ton for the lowest grades of copper-bearing scrap that require re-smelting and refining (Kusik et al 1978).

For this assessment, all processes (from mining through copper wire production) have been combined into one copper production characterization. Inputs and outputs (including emissions) are provided in Table D.4.17. No recycling (only primary copper production) was assumed for this analysis.

8.2.1.5 Other Metals

Two other metals -- zinc and magnesium -- were evaluated in the course of this study. They were not fully characterized because they are used in such small quantities in vehicles. The processes are described below, but because they were not fully characterized, no tables are found for these metals in Appendix D.4. Powder metal was also not characterized.

Zinc. The quantity of zinc per automobile has decreased to under 20 lb. per car, and is not expected to grow. Much of this is used for galvanization of steel parts, and is extremely difficult to recycle. Zinc, like copper, is smelted from domestic sulfide ores. The same considerations concerning sulfur dioxide emissions therefore apply. The energy for production and recycling are approximately 96×10^6 Btu/ton and 7.2×10^6 Btu/ton, respectively, excluding fabrication.

Magnesium.⁶ Although only about 6 pounds of magnesium are used in a typical U.S. automobile, usage is expected to increase as automakers find ways to substitute this extremely light metal for iron and steel and even aluminum in an effort to reduce vehicle weight. With a density of 1.74 g/cc at room temperature, it is 36% lighter per unit volume than aluminum (Al), and 78% lighter than iron (Fe). Magnesium, when alloyed, has the highest strength-to-weight ratio of all of the structural metals. Most current uses are die castings, such as motor housings, but structural uses of wrought magnesium, such as spaceframes, are possible in the future.

Magnesium (Mg) is the eighth most abundant element in the earth's crust, but, because of its reactive nature, it is never present naturally in the uncombined state. Magnesium compounds occur both as solid deposits and in solution in surface waters of the earth. Concentrated aqueous solutions in the form of brine deposits occur at several places in the world, but by far the largest deposit is in the world's oceans. The Mg content of the ocean is 0.13%, which is a smaller concentration than the lowest grade deposit of minerals. However, the ocean represents a virtually unlimited supply, and the uniformity of the magnesium content permits highly standardized procedures to be used for its extraction. Seawater is now the main source of Mg.

Although many processes have been developed to produce metallic Mg, 70-80% of present output is made by electrolytic reduction of $MgCl_2$. The two largest producers of magnesium in the world, the Dow Chemical Company (USA) and Norsk Hydro (Norway), use electrolytic processes that differ mainly in the degree of hydration of the $MgCl_2$ and the cell characteristics.

Magnesium can be recycled, but very little post-consumer material is currently recycled. Data on emissions from secondary magnesium smelting are very poor. Emissions include hydrochloric acid (HCl) from reaction of the flux with moisture in the air, particulate magnesium oxide (MgO) emitted during melting, and some nitrogen oxides and carbon monoxide. Particulates are generally controlled with a baghouse to reduce emissions from secondary smelting from 4 lb/ton to 0.4 lb/ton. Similar emissions would be expected from fabrication in primary and secondary production processes. Additional emissions would be expected from the electrolytic reduction process, possibly including chlorine compounds.

⁶ Magnesium is included in "other" in Tables 8.2-8.7.

8.2.2 Plastics

Plastics comprised about 8% of the mass of the average passenger car produced in 1994 and their contribution to the vehicle shell mass is assumed in this study to remain relatively constant over time. Plastics are chosen for specific uses on the basis of their physical properties, which differ greatly. Therefore, different materials are chosen for different uses. As innovative materials and uses are devised, the number of materials used has grown. The most important plastics used in automobiles and their total historical and projected usage are listed in Table 8.11.

Very little of the plastic recycled in the U.S. currently comes from automobiles. This is because the variety of plastics used and the number of small parts make the process economics poor. Numerous research projects are underway to develop more economical separation and recycling technology for automotive plastics. While innovations to develop new plastics may improve the initial design, they may hinder recycling. Successful recycling generally requires identification and separation of these materials. Most of the energy to make these materials can be saved by recycling to high-valued products, if the materials are appropriately identified and segregated. For each of the materials, except Polyvinyl Chloride (PVC), over half of the embodied energy can be recovered by combustion. Therefore, combustion is a possible alternative. Some products can be made from recycled mixed plastic, but these products are generally lower in value and displace less energy than recycling to the same material.

This section provides an overview of the processes involved in production of the various plastics used in vehicles. For this EVTECA, the energy used and emissions from the processes that produce three of these important plastics (polypropylene [PP], polyester [PET], and high-density polyethylene [HDPE]) were characterized. As will be seen in Section 8.3, PP is also used in battery production. We then developed a composite plastic characterization for all plastics used in the CV or EV shell. The computation of the value for the composite plastic is further described below in the section below called *EVTECA Process Descriptions and Assumptions*.

Processes Involved in Plastics Production

Most commercial plastics are made from petroleum derivatives or natural gas liquids via a series of chemical processes that yield the fundamental building block or "monomer." The monomer is then reacted with itself or other monomers, often at elevated temperature or pressure or with a catalyst, to form the polymer or plastic, which can then be formed into a final product shape. A generic flow chart for plastic part production and recycling is found in Figure 8.16. More specific flow charts are included below for the three plastics for which inputs and outputs were quantified. More detailed process descriptions for all the plastics can be found in Gaines and Shen, 1980, and in general references such as the Kirk-Othmer Encyclopedia of Chemical Technology (1992).

The following two subsections describe the production of specific plastics and provide information about energy use, emissions, and recycling potential. Two categories of plastics are described: thermoplastic resins and thermosets.

Thermoplastic Resins. Thermoplastic resins can be remelted and reformed, in contrast to thermosets, which form cross-linked polymers when formed and cannot be remelted. Most of the plastic recycled in the US is thermoplastic, in the form of polyester (PET) from soda bottles, and polyethylene (HDPE) from milk jugs and soda-bottle base cups. Four other major plastic materials -- PVC, LDPE/LLDPE, PP, and PS --

**Table 8.11 Plastics Usage by North American Original Equipment Manufacturers
(Top 12 ranked by 1990 use -- Millions of pounds)**

TYPE	1985	1990	1995	2000
Urethane	522	454	493	520
Polypropylene	385	437	522	577
Acrylonitrile Butadiene Styrene (ABS)	325	281	289	290
Polyvinyl Chloride	307	264	288	307
Nylon	200	208	246	305
Polyethylene	178	191	248	336
Polyester Composite (SCM)	163	173	261	335
Polypropylene EPDM Modified	41	101	147	188
Polyester Thermoplastic	77	93	102	110
Polycarbonate	55	89	104	114
Alloy PPO Styrene	66	59	67	72
Acrylic	62	51	59	63

*Source: Market Search, Inc., Toledo, OH

accounted for 25% of sales, but less than 1% of recycling in 1991 (Beck 1992). However, recycling of these materials more than doubled from 1990 to 1991. Several major thermoplastic resins are described below.

- Polypropylene.** Polypropylene (PP) has good surface hardness and high compression, flexural, and tensile strengths. In addition, it has excellent chemical resistance up to 250 degrees F (120 degrees C). These properties make it an ideal choice for many auto parts, including battery trays, clips, covers, and cases, fender liners, fuel tank shields, engine splash shields, and fan shrouds. Automotive carpet is also often made of PP. Use of PP in auto parts has been increasing, and this now represents the largest mass of automotive plastics use. The energy to produce PP is approximately 68×10^6 Btu/ton, mostly in the form of oil and gas. Flow charts for the production of olefins (ethylene, propylene, etc.) and polypropylene are shown in Figures 8.17 and 8.18, respectively. Recycling simply requires remelting at low temperatures, and therefore requires considerably less energy, on the order of 13×10^6 Btu/ton. Cases for lead-acid automotive batteries are generally recycled back to the

same use when the batteries are returned, which is mandated by law in most states. Polypropylene from other parts can be recycled to auto parts, carpets, and industrial fibers.

Emissions from propylene polymerization are in the form of particulates (polymer resin) and gases (mostly the propylene monomer). Pollution control is via the systems for recovery of reactants or products (EPA 1995). Emissions from the entire polypropylene production chain (not included here) occur at petroleum refineries or natural gas processing plants, and large chemical-production complexes. These facilities are located outside of major population centers, and are concentrated on the Texas gulf coast, with a few scattered elsewhere in the U.S.

- **Polyester.** Polyester (PET) is a tough, clear, high-melting-point plastic with good barrier properties. Both thermoplastic and thermosetting types are available. Polyester is often the resin base for the fiber-reinforced plastics (FRP) used in automobile parts. PET is produced from para-xylene, a petroleum refinery product, and ethylene, a hydrocarbon made primarily from cracking of natural-gas liquids, via the series of chemical reactions shown schematically in the flow chart in Figure 8.19. The energy required to make PET is estimated at 97.2×10^6 Btu/ton, including the energy needed to refine the hydrocarbon feedstocks, which accounts for 51% of the input energy (Gaines and Shen 1980). The energy requirements for plastics manufacture are considerably more uniform than those for the other materials discussed in this report because all of the production facilities are relatively new and modern, whereas a large variety of old plants are still in service producing the other materials.

The energy required to recycle PET by chemical methods is about one-third that needed to produce PET from the raw materials (Chem Systems 1980). About 65×10^6 Btu are saved per ton of PET recycled chemically, as compared to discarding the PET. Some automobile parts are made from recycled soda bottles.

Emissions from PET manufacture are primarily VOCs and particulates that are generally controlled in order to recover the valuable material constituents, primarily ethylene glycol and methanol. Actual emissions depend on factors such as the plant type, operation mode, and controls in place. Emission factors reported by the EPA range from 0.36-0.73 grams of nonmethane VOCs per kg of product if spray condensers are used to 3.6-3.9 g/kg if they are not. Particulate emission factors are reported as 0.0003-0.17 g/kg with controls on product storage and 0.4 g/kg without such controls (AP-42, Section 6.6.2 1995).

- **High-Density Polyethylene (HDPE).** Polyethylene is inexpensive and has good moisture-barrier properties. Automotive uses include windshield washer fluid containers and other reservoirs and shields, where it competes with PP. Polyethylene is made from ethylene in a single-step polymerization procedure, in which the pressure, catalyst, and other conditions determine the physical properties of the product. Energy and materials flows for the production of HDPE are shown in Figure 8.20. Production of virgin HDPE requires 73×10^6 Btu/ton, of which 40×10^6 Btu/ton can be recovered by combustion (Gaines and Shen 1980). Oil and gas make up over 80% of the input energy. The energy needed to recycle this material if it is clean is relatively low because the HDPE is simply cleaned, dried, ground, and remelted (Boguski 1993).
- **Acrylonitrile-Butadiene-Styrene (ABS).** ABS is a co-polymer of the three oil-based monomers in its name. It is the third most common plastic used in automobiles; usage is expected to decline slightly over time. The energy required to produce ABS is estimated to be 72×10^6 Btu/ton.

- **Polyvinyl Chloride (PVC).** Automobile seat upholstery is often made of PVC, commonly called vinyl. Wire and cable coatings are also made of PVC. The energy to produce PVC is approximately 51×10^6 Btu/ton. For PVC only 30% of the energy is recoverable by combustion. The chlorine content in PVC lowers the heat of combustion and also causes potential corrosion and emission problems at the waste-to-energy plant, as well as during production processes. Although these problems can be solved, recycling of PVC is strongly preferable to combustion, both on energy grounds and because of public perception of combustion emissions. Recycled PVC is used in non-food bottles, pipe, and fencing.
- **Nylon.** Nylon is strong, chemically resistant, has a low coefficient of friction, and is a good electrical insulator. It is used in tire cord, carpeting, electrical parts, bearings, and gears (often requiring no lubrication). Production of nylon is particularly energy intensive because of the many chemical reactions required to achieve the final product. There are two types of nylons (polymeric amides) that are commercially important. For nylon 66 (polyhexamethylene adipamide), which has the majority of the market, the energy input is estimated to be 181×10^6 Btu/ton, of which only 15% can be recovered by combustion.

Thermosets. Thermosets cannot simply be remelted for recycling. The processes available for recycling include hydrolysis, glycolysis, and pyrolysis, all of which break the polymer down into smaller units that must then be reassembled into useful compounds. Recycling of thermosets requires considerably more energy than recycling of thermoplastics. In the case of pyrolysis, the product is a mixture of gaseous and liquid compounds that is probably only suitable for use as a fuel. Used thermosets can also be burned directly as a fuel, for instance as part of auto shredder fluff. Two thermosets used in vehicle manufacture are described below:

- **Polyurethane.** Polyurethane (PU) historically made up the largest mass of plastic used in automobiles, but has been surpassed by PP. However, because much of it is in the form of foam, PU still represents by far the largest volume of plastics in automobiles. Usage is expected to remain steady. Polyurethane foam is used to pad automobile seats and dashboards. Although several experimental techniques have been investigated for recovery of PU foam, no technique has achieved large-scale commercial success. In addition, polyurethane reaction-injection-molded elastomers have been used in auto fascias, bumpers, and fender extensions, and reinforced elastomers have been used in fenders and body panels.

Polyurethane is not a single chemical compound; rather it is a family of compounds containing urethane or carbamate groups (NHCOO) in long chains. They are obtained by reaction of diisocyanates compounds with polyols, such as ethylene glycol, and made by thermosetting by secondary cross-linking reactions. No information on energy use or emissions has been found. The isocyanates and catalysts are highly reactive and must be treated with caution, but their reactivity with water precludes significant environmental effects.

- **Sheet-Molding Compound (SMC).** SMC is a glass-reinforced polyester thermoset with good surface qualities and sufficient strength and rigidity for structural applications. Body panels for vans are often made from SMC. The ingredients are 20-25% by weight polyester resin (one type of which was described above), inert filler such as calcium carbonate to reduce costs and improve material flow characteristics, and glass fibers. Production of hoods made of SMC is reported to require 49.4×10^6 Btu/ton (SMC Automotive Alliance), slightly more on a unit weight basis than steel. However, parts

made of SMC are lighter than the equivalent steel part and there is less manufacturing scrap, so the total energy for SMC part production is estimated to be 60% that for steel part production.

Several processes have been proposed for recycling of SMC, but all result in recovery of lower-valued, lower-embodied-energy products. When reinforced plastics are recycled, the material is often simply ground up for use as filler. This is a clear case of downcycling, with the material displacing glass or other lower-embodied energy materials. Similarly, solvent and pyrolysis processes generally result in lower energy recovery than recycling to the same material. Recycling to the same material, i.e. displacing some of the resin as well, maximizes the energy recovered.

EVTECA Process Descriptions and Assumptions

Energy inputs and emission outputs were characterized for the processes that produce three plastics: PP, PET, and HDPE. Table 8.12 shows the energy and emission values for the three processes. Emissions are primarily associated with fuel combustion and were estimated using standardized emission factors for combustion (previously described above). Oil was assumed to be the fuel consumed. Energy values represent "energy foregone" values derived from Gaines and Shen (1980.)⁷

A composite plastic was characterized by weight-averaging the values for the three plastics, as shown in Table 8.12. Weights were based on the relative shares of the three plastics projected for the year 2000 (see Table 8.11). This composite was employed in the characterization of emissions from plastics used in vehicle manufacture. The final values are also shown in Table D.3.18 in Appendix D. Polypropylene and polyester are inputs to battery production (see Section 8.2 below), so those two plastics are also characterized separately (see Tables D.4.19 and D.4.20 in Appendix D.)

No plastic recycling was assumed to occur.

8.2.3 Other Materials

Other materials of significance in vehicle manufacture include rubber and glass. These two processes are described in this section.⁸

8.2.3.1 Rubber

Rubber comprised a little more than 4% of the mass of the average passenger car in 1994 (Table 8.7). Styrene-butadiene rubber (SBR) is made from 75% butadiene and 25% styrene (by weight), and is used for production of tires and other auto parts, such as gaskets and fan belts.

Processes Involved in Rubber Production

SBR is produced via the cold emulsion process, which is represented in Figure 8.21.

⁷Energy foregone is the difference between total energy input to the plastics production process (both feedstock and fuels energy) and the energy that would be produced if the plastics were burned for combustion. It represents what must have been used up to make the product.

⁸ Fluids and miscellaneous other materials, which make up less than 8% of total vehicle mass, were not evaluated in this analysis.

Table 8.12 Energy and Airborne Emissions per Ton of Plastic Output

	Polypropylene	Polyester	High Density Polyethylene	Weighted Average
Energy (10⁶ Btu/ton)	28.4	74.6	33.0	42.8
Residuals (lbs/ton)				
NOx	5.4	14.2	6.3	8.2
SOx	30.0	79.0	35.0	45.0
TSP	2.64	7.04	3.0	4.0
CO	0.9	2.2	1.0	1.3
VOC	0.05	1.54	0.06	0.49
CO₂	5,200.0	13,600.0	6,000.0	7,817.0
Methane	0.19	0.5	0.22	0.29
Lead	0.0008	0.0021	0.0009	0.0012
Other				
Gas (Propylene)	0.4	0	0	0.2
Share of Year 2000 Plastic	0.24	0.14	0.1	

Several processes are available for recycling of discarded tires, but manufacturers are very reluctant to risk potential decreases in product quality. Incorporation of rubber into paving asphalt offers the greatest potential for energy recovery. This is an example of a open loop recycling option having greater energy benefits than the closed loop (Gaines and Wolsky 1979).

EVTECA Process Descriptions and Assumptions

Inputs and outputs, including emissions for SBR production, are provided in Table D.4.21. No recycling process was included in this analysis. Derivation of the estimate for rubber is based on the same report as for plastics.

8.2.3.2 Glass

Use of glass in automobiles has been essentially constant historically, and is expected to remain so. Glass accounted for a little less than 3% of the mass of the average vehicle built in 1994 (Table 8.7). The main uses are windows and mirrors, for which few materials are able to compete. For these uses, there is some possibility of competition from clear plastics like polyvinyl chloride, but PVC is three times as energy-intensive as glass on a weight basis, must demonstrate the required mechanical properties, and faces public disapproval on perceived environmental grounds. For now, at least, the window and mirror market for glass in automobiles seems assured. In addition, some glass is used as the reinforcing material in reinforced plastic auto parts. Growth in this market is possible.

Processes Involved in Glass Production

The basic steps are the same for production of glass from virgin raw materials or from cullet: raw materials are brought to the plant, prepared, melted at high temperature (2400-2900°F), and formed into products, in this case by floating on a bath of molten tin. The main differences between the processes for new and recycled glass are the supply and preparation pathways for the materials and the additional energy required in the melting process for the endothermic chemical reactions of virgin raw materials to form glass. Process descriptions are contained in two recent reports (Gaines and Mintz 1993 and Babcock, et al. 1988).

New glass is made from sand (silica), limestone (CaCO_3), soda ash (Na_2CO_3), feldspar (aluminum silicates with potassium, sodium, calcium, or barium), and small quantities of other additives. Because CO_2 is generated by the chemical reactions that form glass, 1.15 tons of raw materials are required per ton of new glass.

Cullet (recycled glass) for float glass production is from in-house rejects only. (No post-consumer glass is used.) Increasing the use of cullet in glass furnaces has several advantages. Cullet is reported to act as a flux, aiding the melting of the batch. Less energy is required to melt cullet than to melt and react the batch materials, which reduces combustion-gas emissions. The temperature of the melt is lower, and operation at lower temperature increases furnace life, thereby decreasing production costs. In addition, less dust is produced, and less CO_2 is generated from the chemical reactions of the batch. Production of container glass from 100% cullet has been demonstrated, and routine operation at 70-80% cullet is common. Production of glass from cullet theoretically requires one ton of input per ton of output because the process is simply melting, with no chemical reactions occurring.

Figure 8.22 shows flows for glass products made from virgin raw materials that are used and sent to landfills. Note the recycling loop within the manufacturing plant; this loop represents rejects that are returned

to the process. Such internal recycling is standard practice, makes good economic sense, and is included even when no post-consumer recycling occurs.

Glass for automobile uses (e.g. for vehicle windshields) is generally produced by the float process, in which a thin sheet of glass is formed by flotation on a molten tin bath, under nitrogen atmosphere. Windshields are generally made from two sheets, laminated with a polyvinyl butyryl (PVB) plastic layer between them to prevent shattering in a crash. (This layer would simply burn off in recycling.)

Glass fiber is also used in vehicle manufacture; a specific use is in the manufacture of EV batteries (discussed in depth in Section 8.3 below). Glass for fibers is produced in a similar process to that for windshields, but the molten glass is forced through small openings to form it into fibers, which can then be wound onto spools or cut into manageable lengths, depending on the thickness and the intended use.

EVTECA Process Descriptions and Assumptions

In the EVTECA, we assumed windshield and mirror glass was produced using the float process from virgin materials and in-house cullet. Table D.4.22 in Appendix D shows the inputs and outputs estimated for float glass production of flat glass (the type of glass we used as the typical input to vehicle manufacture). The major energy inputs are natural gas and electricity at the glass plant (gas for melting and annealing, electricity for forming) and coal and natural gas for raw-material mining and processing. Approximately 72% of this energy is in the form of natural gas, and almost all of the rest is electricity. The total energy consumed in flat glass processing is approximately 20.7×10^6 Btu/ton of final flat product and 22.3×10^6 Btu/ton for fibers (based on Babcock 1988).

For glass fiber production (Table D.4.23), the energy input mixture is about 50% gas and 50% electricity (on a Btu basis, when electricity is converted at 10,500 Btu/kWh).

Fugitive dust and raw material particles from raw-material handling are controlled by moist handling or by fabric filters on enclosed transfer points. Emissions from melting and refining may include volatile organics, raw-material particles, and combustion gases; these are controlled by fabric filters. Particulates are the main emissions from fiber-forming. Boron and fluoride emissions may result from the special chemical composition of fiberglass.

8.3 EV Battery Materials

This section provides information about the production of materials that comprise EV batteries. Although the designs and processes are still in flux, and much of the information is proprietary, studies of health and environmental effects provide some data on battery materials and their handling. This section summarizes available information on the materials in four types of advanced electric vehicle batteries: advanced lead-acid (Pb-acid), sodium-sulfur (Na-S), nickel-cadmium (Ni-Cd), and nickel-metal hydride (Ni-MH).

Several observations about battery materials apply to all four types to varying degrees. First, and most obvious, is that the batteries will make up a significant fraction of the EV mass (~20-40%). The impacts are magnified by the fact that some of the batteries are expected to have shorter lifetimes than the vehicles, and therefore will need to be replaced at least once. (See Section 8.1.) When it comes to EVs, battery designers are considering battery recyclability at the design stage. In contrast to the small consumer cells where recycling consists of simply chopping up and processing old batteries, electric vehicle batteries will be large enough to

warrant consideration of disassembly and material segregation (manual or automated) as the first step in recycling. However, work on appropriate methods for reclaiming some of the materials is at best incomplete.

Regarding the materials mixes in advanced batteries, the electrode and electrolyte materials for all types except advanced lead-acid are non-standard automobile materials (although some cadmium has been used historically in coatings and pigments), for which little process information is readily available. However, a significant fraction of the battery mass is made up by casings, separators, and connectors, which are generally made of more common materials like steel and polypropylene. Since these are well-characterized, the uncertainty in impacts from the batteries is reduced.

Production of materials for batteries causes process emissions, resulting from physical and chemical processes carried out on the materials, and emissions from combustion of fuels to drive these processes. The process emissions are different for each material, and are discussed in the sections about specific material production. The emissions from fuel combustion are standard combustion products.

This section is divided into four sub-sections based on the four main types of batteries: advanced lead-acid (Pb-Acid) in Section 8.3.1, sodium-sulfur (Na-S) in Section 8.3.2, nickel-cadmium (Ni-Cd) in Section 8.3.3, and nickel-metal hydride (Ni-MH) in Section 8.3.4. Each sub-section describes the battery design and its components. The battery weights for each EV characterized in the EVTECA are shown in Tables 8.4-8.6 (in Section 8.2 above); the derivation is described in Appendix D.3. Weights are shown in Tables 8.4-8.6 for an individual battery (vehicle battery) and for the entire vehicle lifetime (lifetime battery), which requires one or two battery replacements (depending on the battery type).

The recycling paths for each type of battery are also briefly described in the sections below. However, in the scenarios considered in this study, no recycling is assumed to occur, except for lead, where we do include the secondary lead production process in the EVTECA (but we do not include emissions from the battery recycling process itself.) The individual processes involved in battery production that are included in the EVTECA are described below. The details of the inputs and outputs of each process are documented in Appendix D.4. When more than one process provides the same output (such as primary and secondary lead production processes), the sections below contain a subsection called "Scenario Information" that explains how the process splits were derived.

8.3.1 Advanced Lead-Acid Batteries

Lead-acid batteries are currently used for automotive electrical systems, and therefore some information about their production is available. These are also recycled commercially. The production and recycling processes for materials in conventional lead-acid batteries can be used with minimal changes for advanced EV batteries. Therefore, materials, energy use, and emissions from manufacture and recycling of these batteries can be estimated.

Because even advanced lead-acid batteries have the lowest energy density of the batteries considered, they use the largest mass of materials. At 50 Wh/kg, a 25-kWh battery module would weigh 500 kg (1100 lb). The manufacturing equipment for these batteries is being developed, but the infrastructure already in-place can be used to recycle them.

In the EVTECA, we assume lead-acid batteries are replaced twice during vehicle life of the EV.

Recycling. Over 98% of spent auto batteries in the U.S. are currently recycled (Minerals Yearbook 1993), and over 90% of the lead and lead oxides from batteries is recycled or exported for recycling. These materials are processed by secondary lead smelters, which provide about 2/3 of U.S. lead supply, but there are some uses that require the purer primary product. Approximately 80% of secondary lead is used to produce new automotive batteries. In an operating lead-acid battery recycling plant, the batteries are dismantled mechanically. The top of the battery is sheared off and the acid drained. The lead is separated out as metallic, oxide, and sulfate fractions, and recycled to new electrodes. The casings and plate separators are segregated; the polypropylene case fragments are recovered by a sink/float process and recycled to new battery cases or other products like plastic piping. The acid is cleaned by solvent extraction and reused. It can also be used to neutralize KOH or to make sodium sulfate crystals, for the manufacture of soap. The glass mats from advanced lead-acid batteries reportedly can be recycled. Plant emissions are controlled to meet EPA and OSHA regulations; the plant discharge contains less than 200 ppm SO₂ (Leiby 1993).

Processes to recover lead from the sulfates (and reduce sulfur emissions) have been under development. Paste containing lead sulfate and lead oxide can be desulfurized with soda ash to produce marketable sodium sulfate; the desulfurized paste can then be processed in a reverberatory furnace or electrowon. Electrowinning could be used to improve lead recovery rates and produce a higher-purity product. R&D on this process is ongoing; recent papers include detailed process descriptions and estimates of energy use for secondary lead recovery by electrowinning. The energy required is approximately 6.7×10^6 Btu/ton (Lee 1988), somewhat higher than the energy required by secondary smelting. However, this process recovers material that could not be easily treated in a secondary smelter. Lead emissions from hydrometallurgical processes are likely to be lower than those from pyrometallurgical processes.

Processes Involved in Lead-Acid Battery Production

The Horizon EV battery, developed by Electrosources of Austin, Texas and BDM Technologies, is an advanced lead-acid battery, which was slated to begin limited commercial production in 1995. This battery has an energy density of over 45 Wh/kg. It uses electrodes produced by co-extruding "an alloy of lead onto a high tensile strength core material, making a small diameter, dimensionally stable wire that is woven into lightweight bipolar mesh grids" (Electrosources 1993). The core can be graphite or fiberglass (Moore 1994). The electrodes are then coated with a proprietary paste and assembled horizontally into batteries. The paste is reportedly made from refined lead dust and dilute sulfuric acid. For the negative electrodes, a small amount (~1%) of carbon black, barium sulfate, and lignin-sulfonate is added. For the positive, about 0.03% of a polymer, such as polypropylene, or possibly glass fiber, is added (Geomet 1993). There are fiberglass mats between the porous electrodes to separate them and hold the acid electrolyte, which is all absorbed in the mats and electrodes.

Table 8.14 shows the material composition of the advanced lead-acid battery. These estimates were supplied by the manufacturer (see Geomet 1993). The table also shows energy intensity of these materials, both under their virgin and recycled production conditions. The principal material in the battery is lead, which can be produced in primary or secondary lead processes. Primary lead production in the U.S. is concentrated in Missouri, which accounts for 75% of production. Secondary smelting and battery recycling are more geographically spread, and may occur near population centers. Energy required to produce primary lead was earlier estimated to be roughly 23.4×10^6 Btu/ton (Hudson 1981). That report estimated secondary lead production to require 9.5×10^6 Btu/ton, compared to a more recent estimate of 4.6×10^6 Btu/ton (Leiby 1993) for the smelting step alone at a modern smelter. It is expected that primary production energy has been reduced also. Other components of the advanced lead-acid battery are lead oxide, acid, and fiberglass mats. The containers/covers are generally polypropylene (PP). (Although steel can also be used for the containers, this

assessment assumes PP is used. Aluminum trays have also been considered, but lightweight steel was determined to be less expensive.)

Table 8.14 Advanced Lead-Acid Battery Materials and Energy

MATERIAL	WEIGHT %	PRODUCTION ENERGY (10⁶ BTU/TON)	RECYCLE ENERGY (10⁶ BTU/TON)	ENERGY PER 25 KWH VIRGIN BATTERIES (10⁶ BTU)	ENERGY PER 25 KWH RECYCLED BATTERIES (10⁶ BTU)
Lead	69	23.4	4.6	8.9	1.8
Electrolyte	22				
Sulfuric Acid (pure)	7.9	0.5 (est.)	N.A.	0.02	0.02
Water	14.1	0.03	N.A.	0.00	0.00
Case and Cover (polypropylene)	6.1	68	13	2.3	0.44
Separators (glass mat)	2.1	22.3	18.9	0.25	0.22
Other	0.8	30 (est.)	N.A.	0.13	0.13
TOTAL	100			11.7	2.5

EVTECA Process Descriptions and Assumptions

The weights of each of the components shown in Table 8.14 were used to characterize the mix of inputs to the advanced lead-acid battery production process. Each of the components of the batteries is described as follows:

- Primary Lead Production.** Primary lead is produced from sulfide ores by sintering, reduction in a blast furnace, and refining to 99.99+% purity. A typical process flow sheet, including emissions, is shown in Figure 8.23. As is typical for smelting of sulfide ores, the primary effluent is SO₂. Of this, nearly 85% is produced during sintering. Half of the remainder is captured in the slag; most of the rest is recovered from the blast furnace. Most of the impurities are entrained in the slag. In addition, lead compounds, such as oxides, are released as particulates during both primary and secondary (recycling) lead smelting operations, and during battery manufacture and recycling. Both sulfur oxides and lead are serious health and environmental concerns, and regulations in the U.S. have generally resulted in careful control of these emissions. Older plants not meeting standards have been forced to close by the EPA. Particulates are usually controlled with a baghouse, with control efficiencies exceeding 99%. Sulfur dioxide is recovered and converted to sulfuric acid (see bullet on sulfuric acid, below). Emission factors reported for primary lead smelting are lead: 0.034 kg/tonne

(0.07 lb/t), and uncontrolled SO₂: 23 kg/tonne (45 lb/t). Table D.4.24 (in Appendix D.4) documents the inputs to and outputs (including emissions) from primary lead production..

- **Secondary Lead Production.** Secondary lead smelting re-processes used lead. A flow diagram is shown in Figure 8.24. Controlled lead emissions from secondary smelting are approximately 0.15 kg/tonne (0.29 lb/t), and uncontrolled SO₂ emissions: 40 kg/tonne (80 lb/t). However these are based on very limited data (EPA 1995). Fugitive emissions may be somewhat higher, but no actual data are available. The fuel/reductant in the blast furnace is metallurgical coke (8-14% of the charge); emissions from coke production are not discussed here, but are included in the EVTECA (see Section 8.21). Table D.4.25 shows secondary lead inputs and outputs used in the EVTECA.
- **Sulfuric Acid Production.** The electrolyte in lead-acid batteries is 22-26% sulfuric acid (H₂SO₄), generally made by combustion of sulfur to sulfur dioxide (SO₂), further oxidation to sulfur trioxide using a vanadium-based catalyst, and absorption into strong sulfuric acid followed by dilution to the desired concentration. Most elemental sulfur in the U.S. is a byproduct of oil and gas extraction. Alternatively, byproduct SO₂ from smelting of sulfide ores (e.g., lead sulfide) can be the raw material. In either case, the reactions are highly exothermic, and fuel purchases are generally not required (except small quantities of natural gas during startup). A flow chart of a modern dual-absorption plant for producing sulfuric acid is shown in Figure 8.25. The tail gas from the final absorption tower may contain small quantities of SO₂, and even smaller quantities of SO₃. Older single absorption plants can achieve SO₂ emission levels of 27 lb/t H₂SO₄ (97.9% conversion), and newer dual-absorption plants can meet the 4 lb/ton NSPS (99.7% conversion). H₂SO₄ mist from the stack is generally controlled with demister pads or mist eliminators that reduce emissions by more than 95% (Buonicore 1992). Emissions from sulfuric acid production are presented in Table D.4.26 in Appendix D. Sulfuric acid is generally produced where metals are smelted from sulfide ores, well outside population centers.
- **Polypropylene (PP) Production.** The PP process was previously described in Section 8.2.2. Emissions from propylene polymerization, shown in Table D.4.19, include particulates (polymer resin) and gases (mostly the propylene monomer). Emissions from the entire polypropylene production chain (not included in this EVTECA) occur at petroleum refineries or natural gas processing plants, and large chemical-production complexes. These facilities are located outside of major population centers, and are concentrated on the Texas Gulf Coast, with a few scattered elsewhere in the U.S.
- **Fiberglass Production.** The production of fiberglass is very similar to that of container or float glass (sheet) discussed above in Section 8.2.3.2, except for the final fabrication step. A process flow chart is shown in Figure 8.26. The raw materials, mainly sand, limestone, and soda ash, are transported to a plant where they are melted at high temperature and the formed into fibers. Energy required to produce fiberglass, including energy to produce and transport the chemical inputs, is estimated to be 22.3×10^6 Btu/ton, mostly in the form of natural gas. Energy to recycle would be somewhat lower, about 18.9×10^6 Btu/ton, but is not clear that sufficiently clean material could be separated from battery scrap. Fugitive dust and raw material particles from raw-material handling are controlled by moist handling or by fabric filters on enclosed transfer points. Emissions from melting and refining may include volatile organics, raw-material particles, and combustion gases; these are controlled by fabric filters. Particulates are the main emissions from fiber-forming. Particulate emissions are common to all glass manufacture; boron and fluoride emissions result from the special chemical composition of fiberglass. Emissions from glass fiber production are shown in Table D.4.23 in Appendix D.

Table 8.15 shows rates of airborne emissions from production of lead-acid batteries, including emissions from the manufacture of the metal and plastic constituents of the batteries discussed above. (These are compared in the table emission rates for other battery types discussed in the following sections.⁹)

Table 8.15 Aggregate Airborne Emissions* from Battery Production Segments

Emission Type	Emissions (lb) per 1000 lbs of Finished Battery, by Battery Type			
	Lead-Acid	Sodium-Sulfur	Nickel-Cadmium	Nickel-Metal-Hydride
NO _x	2.21	10.8	6.69	6.85
SO _x	6.13	22.7	637	474
CO	0.154	57.4	12	28
Pb	0.915	0.000708	0.00469	0.0016
TSP	0.733	4.74	4.41	3.21
CO ₂	989	6210	4290	4544
CH ₄	0.0171	0.373	0.189	0.217
NM VOC	0.0372	0.316	0.282	0.228

* Includes basic battery module assembly and manufacture of metal and plastic constituents from raw materials.

Scenario Information

The EVTECA assumes that 75% of the lead in batteries is from secondary lead production, with the other 25% from primary lead production. This is based on approximate historical patterns of use in lead-acid battery production.

8.3.2 Sodium-Sulfur Batteries

The Ford Ecostar is projected to use a sodium-sulfur battery, and the Audi Quattro will use it as part of its hybrid design. The sodium-sulfur battery operates at high temperature (at least 300-350° C), and the temperature must be maintained by insulation or heating from an outside source if the battery is not used daily.

⁹The aggregate emission factors for the battery types are driven by the emission factor of their primary constituents: lead (for Lead-Acid), Ceramics (for Sodium-Sulfur) and Nickel or Nickel Hydroxide for Nickel-Cadmium and Nickel Metal Hydride. Ceramics has a relatively high NO_x emission factor, so the sodium-sulfur battery has the highest NO_x factor. Nickel has a high SO_x factor, so the Ni-Cd and Ni-M-H batteries have high SO_x factors. CO emissions are dominated by the steel emission factor; the Na-S battery uses the most steel. Lead emissions come from lead and copper constituents. The lead-acid battery uses the most lead, and the Ni-Cd battery uses more copper than the Ni-M-H battery. TSP emissions come from nickel, copper and ceramics; only the lead-acid battery uses little of those constituents. Emissions of CO₂ are highest from nickel and ceramics; lead-acid batteries uses none of these. Emissions of both CH₄ and VOCs come from many processes, but the factors for lead-acid battery constituents are much lower than the others.

The battery is targeted for 1000-cycle life, but in this assessment we assume the battery would be replaced once over the vehicle life.

The positive electrode is made of molten sulfur (graphite felt impregnated with S), and the negative is molten sodium. The sodium is extremely reactive, and so containing the materials is a crucial element of the battery design. Safety and regulatory issues are discussed in a recent series of reports by NREL (Ohi 1992 and Corbus 1992).

The battery consists of multiple cells. Each contains a solid ceramic beta-alumina electrolyte, produced by electrophoretic deposition or isostatic pressing; this is sealed to an alpha-alumina component that insulates, with a glass seal on the electrolyte tube. The individual cells are housed in cylindrical metallic cell casings (Al or steel tubes), arranged in an array, with as many as 2000 in a double-wall thermal vacuum box. Banks of cells may be connected by mild steel plates. Because the battery operates at high temperature, plastics cannot be used for the cell casings. The housing, with modules placed in steel or aluminum outer double-wall, evacuated cylindrical containers, represents a large fraction of the total battery weight. One source describes the thermal enclosure as having a wall spacing of 1", with 0.01" stainless steel sheets separated by fiberglass insulation board (Haskins and Reitz 1986). Other separators are possible.

The energy density in batteries of this type is estimated to be between 80-200 Wh/kg, or about four times that of conventional Pb-acid batteries, so they are relatively lightweight. The specific energy of the cells themselves may be even higher (up to the theoretical 760 Wh/kg), but the thermal enclosure adds considerable mass. At 100 Wh/kg, a 25 kWh battery pack would weigh 250 kg (550 lb). Figure 8.27 shows the sodium-sulfur battery design.

Recycling. Recycling of sodium-sulfur batteries is not economical yet, so batteries completing their useful lives now are incinerated, but the following processes have been developed. Additional details and variants can be found in a German patent filed by Silent Power (1993). The external enclosure is removed, and the strip of cells shredded. The ceramics, graphite, and metal are separated. The reactants are dissolved in a water-filled vessel, and sulfuric acid added. Because the temperature is kept in the relatively low range of 80°C to 130°C, energy consumption for the process is low. The products are hydrogen gas, hydrogen sulfide (which is treated with a small-scale Claus process to get elemental sulfur product), and sodium sulfate (also treated for sale). The stainless steel outer container can be recycled, as can the steel or aluminum cell cases. The ceramic electrolyte could perhaps be used as a filler for concrete. The sulfur has been successfully reused in new batteries in laboratory trials. There are appropriate emissions controls on the processes, and the cost is projected to be \$6-10/kWh to recycle, compared to the current \$40-60. The process is claimed to have no gaseous emissions.

An alternative method to recycle some designs of Na-S batteries is to cool the batteries to 100°C, pour out the sodium through a hole in its chamber, and shred the rest. The sulfur can be recovered, and the sodium is purer than virgin material because of filtration through the electrolyte (Shemmans 1994).

NREL (Corbus 1992) reports that a spent 25 kWh battery would contain 50 kg sodium polysulfides (hazardous) and cites sodium sulfide as a potentially salable product. There are possible environmental objections to recycling of Al, steel, and Cu from batteries.

Processes Involved in Sodium-Sulfur Battery Production

The materials used in production of this type of battery include:

- low-carbon steel,
- stainless steel,
- aluminum,
- copper,
- ceramics,
- sodium and sodium polysulfides,
- chromium,
- sulfur,
- alumina, and
- graphite.

However, the main components are sulfur, sodium, ceramics and steel. Table 8.16 shows the component weights used in this EVTECA and the energy use characteristics of those components. NREL estimates total weight of batteries to be ~40 kg Na and 60 kg S for a 50 kWh battery (Corbus 1992). The estimate used for this assessment puts the relative masses at ~12% S, 6% Na, and 20% ceramics, with most of the remainder steel (DeLuchi 1991). For the EVTECA, only the ceramics and steel components were fully characterized.

EVTECA Process Descriptions and Assumptions

The EVTECA accounts for the production of two main components of the sodium-sulfur battery -- ceramics and steel. The total sodium-sulfur battery weight (see Section 8.1) can be multiplied by the weight fractions in Table 8.3.2 to obtain the total weight of ceramic and steel used in each battery. The steel process was previously described in Section 8.2.1.1. (Low-carbon and stainless steel are assumed to have the same process characteristics as steel described in Section 8.2.1.1.) The ceramics production process is described as follows:

Table 8.16 Sodium-Sulfur Battery Materials and Energy

MATERIAL	WEIGHT %	PRODUCTION ENERGY (10 ⁶ Btu/TON)	ENERGY PER 25 kWh VIRGIN BATTERIES (10 ⁶ Btu)
Sulfur	12	0.8-8	0.03-0.26
Graphite			
Sodium	8	92	2.0
Ceramics	20	20	1.1
Steel	<60	66	<10.9
Fiberglass		22.3	
Other		30 (est.)	
TOTAL			~14.2

- Beta-Alumina Electrolyte (Ceramic Production).** The material used in the electrolyte of the sodium sulfur battery is a ceramic in the sodium aluminate class, $\text{Na}_2\text{O} \cdot \text{XAl}_2\text{O}_3$, where the value of X may vary from 5-11 for the different compounds under consideration. The first few process steps, mining of bauxite, refining, and production of alumina are similar to those used for production of primary aluminum. Therefore, the reader is referred to the flowcharts on primary aluminum production (see Section 8.2.1.3 on production of aluminum for vehicle parts). Energy to produce alumina is approximately 12.2×10^6 Btu/ton. High-purity raw material produces electrolyte with the most desirable properties; this presumably leads to somewhat higher energy requirements. Several of these process steps occur in the countries where the bauxite is mined (e.g., Australia, Jamaica, Surinam, Brazil, Venezuela), so the energy use and emissions also occur there. The ceramic production may add significant additional energy due to high temperatures required. To produce the electrolyte, bauxite is reacted with sodium salts and sintered at 1600°C for 5 minutes to get the correct structure (Rasmussen 1994). After the reaction step, the electrolyte powder is pressed into tubes; there is some release of organic additives during the final heating step. The heating may be accomplished by electrical resistance, but RF induction has also been used, and microwave heating is possible. Energy requirements for electrode fabrication range from $9.3\text{-}30 \times 10^6$ Btu/25 kWh battery assembly (based on Miller 1981). The lower end of the range generally applies for continuous production, but there is wide variation by production route and equipment. Table D.2.27 in Appendix D provides a list of the inputs, outputs, and residuals resulting from Beta Alumina Production. No recycling process for the electrolyte material has been postulated, nor is information available on process emissions or possible production plant locations.

The aggregate emissions associated with Na-S battery production, including the characterized inputs, were shown previously in Table 8.15.

8.3.3 Nickel-Cadmium Batteries

Large nickel-cadmium batteries are commercially available for industrial uses. Although automotive battery design is likely to differ somewhat from industrial designs, some insights can be obtained. Several EV types are planning to use Ni-Cd batteries. These include the Mazda Miata, the Nissan FEV 2-seater, the Griffon van (SAFT battery), and the Peugeot 106 and Citroen AX, hybrids with diesel power generators, and many others. The Chrysler TEVan (Caravan) has been tested with Ni-Cd batteries.

A battery with a life of 2,000 cycles would last 6 to 10 years (Morrow 1995), and therefore might not need replacement over the vehicle's lifetime. In the EVTECA, we assume one battery replacement.

The Ni-Cd battery can operate from -40°C to 80°C . There are few design details in the literature. The active material in the sintered positive electrode is $\text{Ni}(\text{OH})_2$, but the overall composition is ferronickel, with nickel, iron, and sometimes graphite constituents. The negative electrode is cadmium and iron, compact and plastic-bonded. Another design features "fiber-structured" electrodes. Potassium hydroxide (KOH) is used as the electrolyte, and there are thin layers of separators in the array. The case is generally made from nickel-plated steel sheet, with sheet steel lids and bases; polypropylene cases are also possible.

Recycling. There is considerable information available on recycling Ni-Cd batteries because facilities already exist; large Ni-Cd batteries are recycled in Japan, Sweden, and France. The technology for recycling is relatively straightforward because cadmium is low-melting and volatile and can be distilled off at relatively low temperatures for recovery. Because cadmium is toxic, careful control is required and facilities would need treatment and disposal permits. Nickel is now classified as a hazardous air pollutant, and therefore faces tight regulation as well.

One process, which could be used for small batteries as well, is reported to pyrolyze the organics; distill, refine, cast, and mold the Cd; and smelt the remaining ferronickel.

In an industrial Ni-Cd battery recycling process that operated in North Carolina, the batteries were discharged and the electrolyte removed, purified, and reused. The alkaline electrolyte can be used to recover metals from plating solutions. The remainder of the battery was shipped to Sweden, where it is dismantled and the electrodes are separated. The positive electrode is sold to steelworks for input to stainless steel manufacture. The negative electrode is rinsed and placed in a topping furnace where the Cd is distilled at 900°C for use in new electrodes. The steel containers are washed and sold to steelworks; plastic jars are cleaned, ground, and reused in new products such as pipe protectors. Although the Ni-Cd battery is durable and its components are subject to only limited corrosion of hardware components, the nickel electrodes would contain require reduction before reuse. This would be desirable if the market for alloying elements became saturated. One reported failure mechanism is the buildup of carbonates in the electrolyte; in that case partial replacement of the electrolyte (50-70% can be easily removed) could extend the battery's useful life (Smaga, 1994).

In the United States, Ni-Cd and batteries are being recycled by Inmetco, which uses a pyrometallurgical process to produce ingots of alloying elements for use in stainless steel manufacture. However, a rough calculation suggests that the nickel from EV batteries could saturate this market. In addition, the pure metal is a more valuable product (it is not economical to separate from small batteries); the obvious solution is to consider closed-loop recycling processes that return the nickel to batteries. The carbonyl process would produce electrode-quality nickel. Another alternative might be to melt the nickel under vacuum and produce a powder product with a spray. In the Inmetco process, the Cd is fumed off and collected.

Inmetco used to sell the material to a zinc smelter, but they lost the buyer and built their own Cd recovery unit. No information on emissions is available.

Processes Involved in Nickel-Cadmium Battery Production

The energy density of the nickel-cadmium battery is not much higher than that of the advanced lead-acid battery. At 57 Wh/kg, a 25 kWh battery would weigh 439 kg (965 lb). New Ni-Cd batteries are reported to have an energy density of 60-65 Wh/kg (Morrow 1995), which would reduce the weight to as low as 385 kg (846 lb). The electrodes are nonreactive. The positive plates $[\text{Ni}(\text{OH})_2]$ typically may contain 22% Ni (8% minimum) if the nickel is on an iron or graphite substrate. Various designs are possible; other designs use nickel foam as the substrate and therefore use more nickel. The positive electrodes must contain less than 1% Cd, and can possibly be reused. Several sources provide inconsistent estimates of overall material composition. According to Morrow, the average Cd content of the battery is 15% (Morrow 1995).

Table 8.17 shows the percentage weights of the various materials (Geomet, 1993a) assumed for this assessment.

Emissions from battery production and recycling are expected to be small, as can be seen in a recent report (Geomet, 1993). Emissions from virgin material production are likely to be more significant. Total aggregate emissions from production of this battery type and its constituents are shown in Table 8.15 (in a previous section).

EVTECA Process Descriptions and Assumptions

In addition to steel, copper, and plastics (previously described), the two major components of the battery that are included in the EVTECA are described as follows:

- **Cadmium.** Cadmium (Cd) is a byproduct of zinc (Zn) manufacture. The zinc is smelted from sulfide ores, leading to SO_2 emissions that are recovered and used to produce sulfuric acid. It is unclear how much, if any, of the emissions should be attributed to the cadmium. Typically, 3 kg of Cd are produced per tonne of Zn. Between 2% and 10% of the Cd is left in Zn mining and beneficiation processes. In the pyrometallurgical production process, cadmium is volatilized during the zinc roasting step and collected as flue dust, which may be dissolved with sulfuric acid, precipitated using zinc, and remelted into ingots.

An early Bureau of Mines report estimates energy of cadmium production from zinc flue dust at 166×10^6 Btu/ton, and from filter cake at 154×10^6 Btu/ton (Llewellyn 1993). It is not known how overall process energy was allocated to the byproduct, which is lower-melting and therefore could be argued to require less energy to produce. Cadmium is produced in the U.S. in Colorado, Illinois, Oklahoma, and Tennessee. Table D.2.28 in Appendix D shows the input and output of the cadmium production process assumed in this analysis.

Table 8.17 Nickel-Cadmium (FNC Type) Battery Material and Energy

Material	Weight %	Production Energy (10 ⁶ Btu/Ton)	Energy per 25 kWh Virgin Batteries (10 ⁶ Btu)
Nickel	20.2	105	10.2
Nickel Hydroxide	17.4	66*	5.5
Cadmium**	24.6	166	19.7
Cobalt	1.4	80 (est.)	0.6
Steel and copper terminals***	4.1	93	1.8
Electrolyte	17.4		
KOH (pure)	5.22	9.3	0.23
LiOH (pure)	0.70	10 (est.)	0.04
Water	11.48	0.03	0.00
Case and Cover (stainless)	11.7	66	3.8
Miscellaneous Plastics	3.1	R68	1.02
Other	0.1	30 (est.)	0.02
TOTAL	100		42.8

Note: * Assumed produced from pure nickel

** 88% Cd, 12% CdO

*** Assumed 50% Cu, 50% steel for estimation purpose

- Nickel.** Although nickel is produced in the U.S., metal of sufficient purity is only produced at two sites, both outside of the U.S. The nickel used in electrodes for Ni-Cd and Ni-MH batteries is an extremely pure (>99.%) powder form (INCO 123) only produced by one company in the world, at plants in Wales and Canada. A similar material is reportedly being produced in Siberia. It is produced by the carbonyl process, in which carbon monoxide (CO) is reacted with nickel at 120° F to form nickel carbonyl (Ni(CO)₄). The cobalt, copper, and iron impurities are left behind. The nickel carbonyl is decomposed back to nickel at 450° F. Nickel carbonyl is toxic, and so careful process control is necessary to avoid health and environmental hazards. Nickel recovered from spent batteries could probably be recycled to battery-grade material using this process as well. Energy requirements for the carbonyl process are not currently available; a rough estimate for energy required to make virgin nickel from sulfide ores is about 105 million Btu/ton (Kuck 1994). Note that smelting of such sulfide ores produces large quantities of SO₂. The U.S. Bureau of Mines estimates production of 8 tons of sulfur for each ton of nickel (Kuck 1993). Expensive control equipment reduces emissions to much lower levels (1994 levels at one plant have been reduced 93% from 1978 levels),

as mandated by the Clean Air Act Amendments in the U.S. and by other laws abroad. Note that the SO₂ emissions from primary nickel for electrodes occur where the material is smelted overseas. In Canada, Inco has attained compliance with emissions regulations at great expense. Emissions associated with nickel production are shown in Table D.4.29 in the Appendix.

8.3.4 Nickel-Metal Hydride

Small nickel-metal hydride batteries have been commercial since 1987 for use in electronic equipment like computers and telephones. Vehicle batteries are expected to be ready for production in 1996 by GM Ovonic (Troy, MI); Hyundai will use the Ovonic battery in its EV. Other manufacturers are also developing Ni-MH batteries. Ovonic claims that the battery life would be similar to that of the vehicle (Science 1993), so the battery would not need to be replaced, but other estimates suggest that the battery would only last 3-5 years (Morrow 1995). This type of battery does not operate at high temperatures, but does need some cooling because it is sealed and pressurized.

Recycling. No facilities are available yet for recycling nickel metal hydride batteries, except for Inmetco's, which can produce pigs for alloying stainless steel. In this process, Inmetco can recover the Ni, Fe, Cr, and Mn, and part of the V as alloying elements; the rest of the elements go to the process slag for sale as aggregate (Corbus 1993). Because this process does not recover valuable elements like Ti and because the stainless steel market may be too small to accommodate the materials from large numbers of EV batteries, closed-loop recycling, or at least recovery of more valuable separated materials, might be preferable. Since Ni-MH batteries comprise many different technologies and combinations of elements, a generic discussion of recycling processes is of limited value; design-specific analyses will eventually be necessary.

A recent study by NREL (Sabatini 1994) estimated costs, including energy costs, for potential recycling processes for Ni-MH automotive batteries. Direct energy use for the different processes ranges from 4-14 x 10⁶ Btu/ton of batteries processed, almost all in the form of electricity. However, these estimates only include the process steps at the recovery facility, not those at other facilities required to produce products from the separated scrap. In addition, the energy embodied in the material inputs to the processes is not included.

Processes Involved in Nickel-Metal Hydride Battery Production

The positive electrode is composed of nickel hydroxide, Ni(OH)₂. The negative electrode is one of several specially-engineered metal hydrides that are multiple alloy metal matrix composites, using rare earths or vanadium, nickel, titanium, zirconium, chromium, and manganese. These are amorphous, meaning that the atoms are in disarray, rather than being aligned. The electrolyte is 30% aqueous potassium hydroxide, referred to as starved because there is no free electrolyte. Rather, it is all entrained in porous electrodes or polypropylene separators. Therefore, the battery may be classed as "dry" for regulatory purposes. The individual cells are sealed, prismatic containers, typically made of stainless steel. Several different designs are available, differing primarily in the hydride composition; that used by Ovonic is designated as the AB₂ type and that by SAFT the AB₅.

In the Ovonic design, the electrodes are thin flat plates, separated by insertion in porous polypropylene bag separators which are stacked in multilayer sandwiches. A stack of electrodes forms a battery cell (~4x7x1"), weighing 1600 grams. Each cell has two terminals coming out of the top, on small nylon disc spacers. The case is stainless, four mils thick, with a green plastic shrink-wrapped cover. The cells are assembled into six 12-volt modules, which are assembled into the battery-pack trays. The trays would be designed by the auto manufacturer, and could be made of ABS plastic or aluminum.

High energy density of about 70-80 Wh/kg is expected to result in a relatively compact, lightweight battery. A 25 kWh battery would weigh about 330 kg (730 lb). Current technology could raise the energy density to over 120 Wh/kg, and advanced materials and configurations are speculated by the developer to have the potential to achieve up to 500 Wh/kg (Ovshinsky, et al. 1994). Such a major breakthrough could lower the weight of an EV battery pack to about 100 lb.

Published estimates of materials in Ni-MH batteries differ in the quantities of KOH electrolyte, the composition of the hydride electrode (whether or not iron is the substrate for the hydride electrode), and the amount of steel in the case. This is not surprising, since different designs are being considered at this stage. Table 8.18 shows the mix of materials we assume for the EVTECA.

The different Ni-MH battery designs differ mainly in the composition of the metal hydride negative electrode. The AB₅ type uses a rare-earth Misch metal (typically LaNi₅ with naturally-occurring rare-earth combinations that can include Ce, Nd, and Pr) and the AB₂ a vanadium-rich refractory alloy. Relative elemental weights for an AB₂ negative electrode might be 22.7-40.9% V, 20.5-35.9% Ni, 20.2-25.4% Zr, 8.4-16 Ti%, and 0-1 Mn%. The negative electrode powder from scrap AB₅ consumer cells was found to contain typically 33% rare earths, 60% transition metals, and 7% other metals (Mn, Al) by weight (Lyman and Palmer 1994).

The flat plate hydride electrode of the Ovonic battery consists of the amorphous or polycrystalline hydride powder pressed onto a woven nickel grid that serves as its base. The alloy is produced by vacuum induction melting, which is relatively energy-intensive because of the high temperatures required to melt V and Zr. The alloy is very hard and is only partially broken before hydriding. After the hydride is produced, the material can be ground more easily to a powder for pressing onto the electrode.

EVTECA Process Descriptions and Assumption

The nickel electrodes in Ni-MH batteries are essentially the same as those in the Ni-Cd batteries (see Table 8.15). See Section 8.3.3 and Table D.4.29 for the emissions associated with the nickel production process. The metal hydride electrode was not characterized due to lack of definitive information. (Polypropylene, iron, and stainless steel processes, also included in the characterization of Ni-MH batteries, were previously described.)

Table 8.18 AB₂ Nickel-Metal Hydride Battery Materials and Energy

Material	Weight (%)	Production Energy (10⁶ Btu/Ton)	Energy per 1000 lb Virgin Batteries (10⁶ Btu)
Nickel	16.4	105	6.3
Nickel Hydroxide	12.1	66	2.9
Metal Hydride (V, Zr, Ti, Cr, Al)	12.9	100 (est.)	4.7
Separators (polypropylene)	5.0	68	1.2
Electrolyte	9.0		
KOH (pure)	3.0	9.3	0.10
Water	6.0	0.03	0.00
Iron	14.5	38	2.0
Stainless steel	29	66	7.0
Other	1.1	30 (est.)	0.12
TOTAL	100		24.5

8.4 References for Chapter 8

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Figure 8.3 Process for Vehicle and Battery Production

Figure 8.4 Generalized Metal Part Production

Figure 8.5 Steel Production: Energy Cycle Segment

Figure 8.6 Pelletizing, Sintering, Coking and Blast Furnace Processes

Figure 8.7 Basic Oxygen Process for Steel Production

Figure 8.8 Electric Arc Furnace

Total Energy = $5.63 \times 10^6 \text{ Btu} + 305 \text{ kWh} = 8.8 \times 10^6 \text{ Btu/ton Sheet}$

Figure 8.9 Steel Sheet Making

Figure 8.10 Virgin Steel Part Production

Figure 8.11 Wrought Aluminum Production: Energy-Cycle Segment

Recycled Aluminum Production

Virgin Aluminum Production

Figure 8.12 Cast Aluminum Production: Energy-Cycle Segment

Total Energy = $46.2 \times 10^8 \text{ Blu} + 14,794 \text{ kWh}$
 = $157.4 \times 10^8 \text{ Blu/ton Ingot}^{**}$

* Including electrode manufacture and coal to produce coke
 ** Electricity converted to Blu equivalent, with the 43% hydroelectric power converted at 3,413 Blu/kWh

Figure 8.13 Virgin Aluminum Ingot Production

Figure 8.14 Stamped Aluminum Part Production From Ingots

Figure 8.15 Production of Cast Aluminum Parts

Figure 8.16 Generic Plastic Part Life Cycle

*Crude distillation at 390 Btu/lb.

Figure 8.17 Energy and Materials Flow for Production of Ethylene and Its Co-Products
(Source: Gaines and Shen 1980)

Figure 8.18 Energy and Materials Flow for Polypropylene Production

Figure 8.19 Energy and Materials Flow for Polyester Production
(Source: Gaines and Shen 1980)

Figure 8.20 Energy and Materials Flow for HDPE Production
(Source: Gaines and Shen 1980)

Figure 8.21 Energy and Materials Flow for SBR Production
(Source: Gaines and Shen 1980)

Figure 8.22 Glass Container Process Energy and Material Flow for Maximum Use of New Materials (not including extraction and processing energies for fuel)

Figure 8.23 Typical Primary Lead Processing Scheme
(Source: Buonicore 1992)

Figure 8.24 Secondary Lead Smelter Flowsheet
(Source: Leiby 1993)

Figure 8.25 Flow Diagram of Dual-Absorption, Sulfur-Burning Sulfuric Acid Plant
(Source: Buonicore 1992)

Figure 8.26 Fiberglass Manufacturing Process
(Source: Buonicore 1992)