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The University of California Transportation Center

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Impacts of Electric Vehicles on Primary Energy Consumption and Petroleum Displacement

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Abstract--We analyze the impact of the use of electric vehicles (EVs) on energy consumption in general and petroleum consumption in particular. The analysis is conducted for sub-compact cars, small vans, and large vans for the years 1995 and 2010. We compare per-mile primary energy consumption of EVs and gasoline internal combustion engine vehicles (ICEVs), for each of four primary energy sources: petroleum, coal, natural gas, and biomass. When petroleum, natural gas, or biomass is the primary energy source, EVs with current technology will consume more energy per mile than ICEVs, but EVs with advanced technology will consume less. If coal is the primary energy source, both current- and advanced-technology EVs will consume less energy per mile than ICEVs. We find that the magnitude of petroleum displacement by EVs depends mainly on the amount of petroleum used for electricity generation. In many areas of the U.S., EVs will reduce per-mile petroleum use by over 90%, because the vast majority of electricity is generated from non-petroleum fuels. In areas where a relatively large portion of electricity is generated from petroleum (such as New York), EVs will reduce per-mile petroleum use by 65%.

1. INTRODUCTION

The transportation sector accounts for 26% of total end-use energy consumption in the U.S., and 65% of petroleum use, and imported oil is projected to account for about 60% of total U.S. oil use in 2010, up from 42% in 1989.[1] The recent crisis in the Middle East, and the resultant increase in the price of oil in a short period of time, has created new concerns about U.S. dependence on imported oil. Due to its complete dependence on petroleum, the U.S. transportation sector is especially vulnerable to disruptions in the world oil market. Conserving transportation energy and reducing transportation petroleum consumption should become long-term national goals.

The use of electric vehicles (EVs) may reduce energy consumption and petroleum use in transportation. In this paper, we 1) compare the primary energy consumption of EVs with that of ICEVs, and 2) estimate petroleum displacement by EVs.

From the 1973 oil crisis through the synfuels era, several studies examined the energy consumption of EVs, relative to that of gasoline internal combustion engine vehicles (ICEVs) (Table 1). These studies projected the electricity consumption of EVs and the gasoline consumption of comparable ICEVs, and then back-calculated primary energy consumption. These studies came to widely different conclusions, however, primarily because of different assumptions about future EV technologies, power plant efficiency, and the primary energy sources used to produce gasoline for ICEVs and electricity for EVs.

Table 1. Previous studies on EV primary energy consumption

Study	Per-mile energy use (% of ICEVs)	primary energy (EVs vs ICEVs)
Salihi[2]	73.5	Coal vs petroleum
Powell[3]	95	Coal vs coal
	100	Petroleum vs petroleum
Busch et al[4]	55.6-81.7	German electric mix vs petroleum (low speed driving cycles)
	114	German electric mix vs petroleum (high speed driving cycles)
Mueller et al[5]	60	Petroleum vs petroleum
	30	Coal vs coal
Hamilton[6]	103-105	Petroleum vs petroleum
	60	Coal vs coal
Bevilacqua et al[7]	More than ICEVs	Petroleum vs petroleum
	Less than ICEVs	Coal vs coal
Agarwal[8]	250-350	Petroleum vs petroleum (depending on type of battery)
	200-260	Coal vs coal (depending on type of battery)
Margiotta[9]	200	Electric mix vs petroleum

There has not been comparison of energy consumption between EVs and ICEVs since the early 1980s. Since then, EV technology has been improved considerably. The advances in EV technology, and the availability of better data on the energy efficiency of converting primary energy sources to final energy products, make it desirable to perform an updated and detailed analysis.

2. APPROACH

Throughout this paper, the energy efficiency of a process is defined as the energy output from the process divided by the energy input to the process, where input energy includes process energy as well as the energy resource. "Primary" energy is the in-place energy resource: petroleum in oil fields, natural gas in gas fields, coal in coal mining sites, and biomass in the fields, and so on. Final energy products are the energy products, such as gasoline and electricity, that are used directly in vehicles.

We calculate the primary energy consumption of EVs and gasoline-fueled ICEVs in several steps. First, we predict ICEV fuel economy (in miles per gallon, MPG) and EV electricity consumption (in Kwh per mile). Because EV energy efficiency will improve over time, as battery and powertrain technology improves, as will ICEV fuel economy, power plant conversion efficiency, and the efficiency of other conversion processes, we target our analysis for two years, 1995 and 2010, which feature different efficiency assumptions.

Second, we estimate the energy efficiency of converting primary energy sources to final energy products, using data on energy use at each step of the fuel cycle: primary energy production (e.g., petroleum recovery), feedstock transportation, conversion to final energy products (e.g., petroleum refining), and product transportation (e.g., gasoline distribution). And then, we calculate the primary energy consumption of EVs and ICEVs in Btus per mile, and estimate the potential energy savings of EVs.

Finally, we calculate petroleum displacement by EVs, by accounting for petroleum use by electricity generation systems and at other stage of the fuel cycle.

We consider four primary energy sources: petroleum, coal, natural gas (NG), and woody biomass.+ We choose lignocellulosic biomass, rather than crops, because lignocellulosic is more abundant and less expensive. We assume that trees will be grown in plantation fields using short-rotation intensive-cultivation.

The four primary energy sources (petroleum, coal, NG, and biomass) and the two final energy products (gasoline and electricity) result in eight conversion processes: petroleum to gasoline, petroleum to electricity, coal to gasoline, coal to electricity, NG to gasoline, NG to electricity, biomass to gasoline, and biomass to electricity. Of these, we ignore the process of

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[+] Oil shale can be recovered and converted into petroleum liquids, and used to produce gasoline or electricity. Since the extra two stages of the shale-oil cycle (oil shale recovery and conversion) relative to the crude-oil cycle apply to both gasoline and electricity production from oil shale, the inclusion of these two stages would not change EV primary energy consumption, relative to ICEV energy consumption. The relative energy impact of EVs with oil shale as the primary source is the same as the impact with petroleum as the primary source. For this reason, we did not consider oil shale as a separate primary source.

converting NG to gasoline, because NG is more likely to be converted to methanol or compressed NG for transportation use.

The analysis thus includes four types of power plants: oil-, coal-, NG-, and biomass-fired. Although electricity also is generated from hydropower, nuclear, wind, solar, and geothermal power, we did not consider them in the analysis, because there is no parallel way of using them for ICEVs, and because energy consumption in Btu for these sources is less meaningful than for the others.

To be realistic in the comparison of EVs with ICEVs, we choose the types of ICEVs most likely to be replaced by EVs. Studies have shown that subcompact cars, small vans, and large vans probably will be the first to be replaced by EVs.[10-13] Therefore, we analyze EV energy impacts for these three vehicle types, for 1995 and 2010 model year.

3. DATA AND METHODS

3.1. Fuel Economy of ICEVs

The fuel economy of new passenger cars has increased from 15.8 MPG in 1975 to 27.8 MPG in 1990,[14] mostly due to corporate average fuel economy (CAFE) standards.[15] Table 2 shows our fuel-economy assumptions for the three types of vehicles and for two model years. To predict future fuel economy, we start with EPA's laboratory-tested fuel economies for 1990 model-year cars and vans. We adjust these laboratory results to account for the difference between laboratory and on-road fuel economy. Then, we estimate on-road fuel economy for the 1995 and 2010 model-year cars and vans by applying the annual rate of increase in fuel economy implied in the study of Difiglio et al.[16]

Difiglio et al estimated fuel economy for three cases: (1) the manufacturer's product plan; (2) the cost-effective case; and (3) the technologically feasible case. The cost-effective case, which we adopt in our analysis, assumes that the savings in fuel costs over the life of a vehicle (10 years in their study) pays back the cost of MPG-improving technologies. In Difiglio et al's cost-effective case, fuel economy increases by 2.32% per year between 1987 and 2000. We therefore assume an annual rate of 2.32% between 1990 and 2000 for subcompact cars. We assume a rate of 2% between 2001 and 2010, because of increasing marginal costs and diminishing marginal benefits of further increase in fuel economy.

Difiglio et al did not estimate fuel economy for light duty trucks (LDTs). Based on EPA's historical data (1980-88),[14] we calculated the historical annual rate of increase in fuel economy for LDTs, and compared the rate with the historical rate for cars. The historical annual rate of increase was 2.37% for LDTs, and 3.12% for passenger cars, indicating that the ratio of the rate of increase in LDT fuel economy to that in car fuel economy is 0.76 (2.37/3.12). The EIA (Energy Information Administration)[17] estimate that the annual rate of increase in fuel economy for LDTs is a little more than half (0.5) of the rate for cars. We therefore assume that the fuel economy of LDTs will increase 60% as fast as the fuel economy of cars, or 0.6x2.32%=1.39% per year between 1990 and 2000, and 1.2% per year between 2001 and 2010.

The projected fuel economy for three vehicle types is shown in Table 2. We have also presented vehicle weights in Table 2, since, as we shall see, baseline vehicle weight is important in determining the efficiency of the heavier EV (relative to the baseline ICEV).

Table 2. Projected fuel economy (in MPG) and weight (in lbs) of ICEVs

Model-year	sub-compact cars	small vans	large vans
MPG:			
1990(urban cycle)[a]	27.4	19.8	14.9
1990(on-road)[b]	24.7	17.8	13.4
1995(on-road)[c]	27.7	19.1	14.4
2010(on-road)[c]	37.8	23.1	17.3
Lbs:[d]			
1995	2,750	3,850	4,650
2010	2,350	3,450	4,350

[a] Laboratory-tested fuel economy of the 1990 model-year vehicles over the urban cycle.[14] We use urban-cycle fuel economy because the EVs with which the ICEVs are to be compared are tested over EV city cycles, and most likely will be used for city driving.

[b] The urban fuel economy of 1990 model-year vehicles under actual driving conditions. EPA's MPG results are for laboratory conditions, so one must first adjust the laboratory fuel economy to real-driving-condition fuel economy. The EPA has determined that vehicles achieve 10% lower urban MPG under on-road conditions than under the laboratory conditions.[18] We apply this reduction rate to calculate on-road urban fuel economy.

[c] Projected urban fuel economy under actual driving conditions for the 1995 and 2010 model-year vehicles. See the text for the detailed projection.

[d] We assume that the vehicle weight will decrease in the future due to improvements in vehicle component packaging and the application of lighter materials. The projected vehicle weight will be used for estimating the efficiency penalty of EV weight increases.

3.2. Electricity Consumption of EVs

To predict future EV electricity consumption, we estimate EV component efficiencies (powertrain, battery, and charger), and calculate EV efficiency relative to baseline ICEV efficiency. The expression for EV electricity consumption is

$$\text{electricity}_{ev} = 125{,}000/\text{MPG}_{icev}/3412 \text{x} P_{(ev/icev)}/B_{ev}/C_{ev}/(1-W_{ev}) \qquad (1)$$

Where electricity_{ev} is EV electricity consumption in KWh per mile (from the wall outlet), 125,000 is the heating value of gasoline (Btu per gallon), MPG_{icev} is ICEV MPG, 3412 is the energy conversion factor from KWh to Btu, $P_{(ev/icev)}$ is EV energy consumption (battery to wheels) over ICEV energy consumption (fuel tank to wheels), B_{ev} is EV battery efficiency, C_{ev} is EV charger efficiency, and W_{ev} is Efficiency penalty of extra EV weight (relative to ICEV weight).

We next present our estimates of the above components.

3.2.1. Fuel Economy of ICEVs (MPG_{icev}) The above equation couples EV electricity consumption directly with ICEV MPG. This applies only to the measures which can be used to improve efficiency of both ICEVs and EVs. Other measures, such as advanced internal combustion engine technologies, will not have effect on EV electricity consumption. The MPG projected from Difiglio et al's study (presented in Table 2) is from engine improvements, transmission improvements, and the improvements in other components, such as tires, weight reduction, etc. To calculate EV electricity consumption, we exclude the MPG-imprving measures from advances in internal combustion engines. Difiglio et al.[16] estimated that about 75% of the MPG improvements of their study would be from engine technology advances. The remaining 25% of MPG improvments is from improvements in transmission and other vehicle components, and can be applied to improve EV efficiency. And thus, we use 25% of the MPG improvements in Table 2 to estimate EV electricity consumption in 1995 and 2010.

3.2.2. EV Energy Consumption over ICEV Energy Consumption ($P_{(ev/icev)}$) Using existing test data on the energy consumption of EVs and comparable ICEVs, we calculated the ratio of EV energy consumption (from the battery to the wheels) to ICEV energy consumption (from the fuel tank to the wheels) (Table 3). In calculating this ratio, we factored out the effect on efficiency of the extra weight of the EV, because we consider this weight effect separately. To do so, we need to know the relationship between weight and efficiency. Several studies have indicated that a 10% change in vehicle weight causes a 6% change in vehicle efficiency.[19-22]

Table 3. EV powertrain efficiency relative to ICEV powertrain efficiency

EV type	Weight (lbs)	Kwh/mile[a] (from battery)	Driving cycle[b]	Comparable ICEV	Weight (lbs)	MPG[c]	Powertrain ratio[d]	Source
Impact	2200	0.110	city	90'Geo Storm	2000	52.7	0.149	GM[10]
G-Van	8120	0.654	city	90'G30-Van	5000	15.2	0.222	Risser et al[23]
TEVan	4948	0.301	city	90'CaraVan	3250	24.8	0.169	Gosden[24]
DSEP-Van	5300	0.418	FUDS	90'Caravan	3750	20.5	0.200	Burke et al[25]
ETX-I	3800	0.334	FUDS	83'Escort	2375	25.0	0.185	MacDowall et al[26]
ETX-II	4500	0.427	FUDS	90'Aerostar	3750	19.4	0.204	Fenton et al[27]
Griffon	6775	0.602	city	84'G10/G20 Van	4500	16.0	0.217	Driggans et al[28]
Stromer	3671	0.285	SAE C	85'VW Golf	2500	28.7	0.189	Driggans et al[29]
4-seat BMW	3600	0.268	ECE	86'BMW 3Series	3125	23.7	0.161	Angelis et al[30]
ETV-1	3960	0.293	FUDS	79'Horizon	2500	26.0	0.169	Kurtz[31]
ETV-2	3920	0.318	FUDS	81'BMW320	2750	25.0	0.158	AiReserach[32]
Audi	4630	0.435	city	80'Audi100	3500	16.8	0.175	Mueller et al[5]

[a] Some of the studies cited here presented EV electricity consumption not from the battery, but from the wall outlet. To calculate EV electricity consumption from the battery for these studies, we assumed an efficiency of 80% for the charger and 75% for the battery.

[b] "City" means that an EV is tested in urban driving conditions but not for any particular standard driving cycle. FUDS is the Federal Urban Driving Schedule, which is used by the EPA to test urban fuel economy of ICEVs. SAE C has higher demand for average speed and power than the FUDS. The European ECE cycle is a composite of the FUDS and the U.S. highway cycle.

[c] Urban Fuel economy. We obtained the fuel economy for these vehicle models from EPA's test vehicle list for different model-year vehicles.

[d] EV energy consumption over ICEV energy consumption. The ratio is calculated as $\{(\text{Kwh/mile})_{ev}/[1+(\text{weight}_{ev}-\text{weight}_{icev})/\text{weight}_{ev}\text{x}0.6]\text{x}3412(\text{Btu/Kwh})\}/[125{,}000(\text{Btu/gal})/\text{MPG}_{icev}]$. We assume that a 10% reduction in vehicle weight will lead to a 6% increase in vehicle efficiency (see the text).

We have not held vehicle performance constant in this analysis. That is, we have implicitly let the EV have worse performance than the ICEV, as it likely will have. We do this because even though many EVs will in reality have lower performance than ICEVs, in any case the energy impact of substituting one mile of trips by EVs for ICEVs depends solely on the energy characteristics of EVs and ICEVs, not on their performance. The difference in vehicle performance between EVs and ICEVs certainly will determine how many trips can be substituted by EVs for ICEVs, and therefore will affect EV impacts on <u>total</u> energy use in the transportation sector.

The EV relative energy consumption is calculated based on tested results over city driving cycles for both ICEVs and EVs. The EV relative energy consumption would be higher if the tested results over highway driving cycles were used. We use city-cycle results because EVs probably will be used for urban trips.

We do not consider the energy consumption of air conditioning systems. Since the air conditioning system of a gasoline ICEV is not used during the fuel economy test, the exclusion of air conditioning in our comparison should not affect EV energy impacts relative to ICEV energy consumption, unless EV air conditioning systems are very different from ICEV air conditioning systems, which is unlikely.

Table 3 shows that the ratio of EV energy consumption from the battery to ICEV energy consumption ranges from 0.149 to 0.222. We use a ratio of 0.18 for 1995, and 0.15 for 2010. The lower EV relative energy consumption in 2010 is due to improvements in EV powertrain efficiency in the future (e.g., switching from DC to AC motors). Improvements in efficiency are likely because efficiency directly determines the range and operating cost of EVs.

3.2.3. EV Battery Efficiency and Charger Efficiency Our assumptions regarding EV technologies and component energy efficiencies are presented in Table 4. Different battery technologies, such as lead/acid (Pb/acid), sodium/sulfur (Na/S), nickel/iron, zinc/bromine, zinc/air, iron/air, nickel/cadmium, aluminum/air, and lithium-aluminum/iron sulfide, are currently being researched and developed.[33] The 1995 case assumes advanced Pb/Acid batteries, while the 2010 case assumes advanced Na/S batteries.

Table 4. EV technology assumptions

	1995	2010
Battery type	Pb/Acid	Na/S
Energy density of battery (Wh/Kg)	44[a]	110[b]
Battery efficiency (%)	75[c]	80[d]
Charger efficiency (%)	80[e]	92.5[f]
Electric motor type	DC	AC
Relative energy use (EV/ICEV)	0.18	0.15

[a] 45 Wh/kg in Applied Energy Institute (Japan),[34] 40.3 Wh/kg in Kuno (Toyota),[35] and 47 Wh/kg demonstrated by Budney.[36]

[b] 125 Wh/kg in Marr et al,[37] and 100 Wh/kg in Adams et al.[38]

[c] Gosden et al,[39] Budney et al.[36]

[d] Sheladia Associates, Inc..[40]

[e] Belanger et al.[41]

[f] DeLuchi et al.[42]

3.2.4. Efficiency Penalty of Extra EV Weight We adjust the overall EV relative energy consumption to account for the extra weight of the EV in several steps. First, we project the driving range of future EVs (Table 5) based on various studies.[10, 42-46] Using the projected EV range and the assumptions of battery energy density (Table 4), we calculate the battery weight for the three types of EVs: sub-compact cars, small vans, and large vans. We then estimate the increase in overall EV weight by considering the battery weight, the weight reduction in the EV powertrain, and the weight increase due to the structural support of the battery. finally, we calculate the EV efficiency loss due to the extra weight by assuming a 6% decrease in vehicle efficiency for a 10% increase in vehicle weight, as discussed above.

3.2.5. Calculation of EV Electricity Consumption from the Outlet With the preceding results, we calculate EV electricity consumption in Kwh per mile from the electric outlet (Table 5).

Table 5. EV characteristics and energy consumption

EV performance item	Sub-compact car		Small van		Large van	
	1995	2010	1995	2010	1995	2010
Driving range (Miles)	100	200	100	200	80	150
Extra weight (lbs)[a]	1233	585	1788	1007	1782	875
Efficiency Loss factor (%)[b]	18.6	12.0	19.0	13.6	16.6	10.1
ICEV EC/EV EC[c]	2.62	4.04	2.62	4.04	2.71	4.25
Kwh/mile (from the outlet)[d]	0.55	0.32	0.77	0.48	0.99	0.60

[a] EV extra weight=battery weight+(EV powrtrain weight-ICEV powertrain weight)+extra EV structure weight. Battery weight is calculated through an iterative process as weight = range $(\text{miles})\times(\text{Kwh/mile})_{ev}/(\text{Kwh/Kg})_{battery}$.

[b] EV efficiency loss factor due to extra weight. Calculated as $(\text{weight}_{ev}-\text{weight}_{icev})/\text{weight}_{ev}\times 0.6$. The weight of ICEVs is from Table 2.

[c] ICEV energy consumption from the fuel tank over EV energy consumption from the electric outlet, which is calculated as 1/(EV energy consumption relative to ICEV energy consumption) x battery efficiency x charger efficiency x (1-efficiency loss factor for extra EV weight).

[d] EV electricity consumption in Kwh/mile from the electric outlet is calculated as 125,000 (Btu/gal) / MPG_{icev} / (ICEV EC/EV EC) / 3412 (Btu/Kwh). The calculation of ICEV MPG is presented in section 2.2.1.

The results, presented in Table 5, indicate large reductions in EV electricity consumption per mile between 1995 and 2010. These reductions are due to changes in battery technology, improvements in EV powertrain efficiency, improvements in charger efficiency, and improvements in ICEV fuel economy (EV efficiency is estimated relative to ICEV fuel economy). A sensitivity analysis on the ranges of these four parameters between 1995 and 2010 showed that changes in EV battery technology contributed to 45% of the reduction; improvements in powertrain efficiency, 24%; improvements in charger efficiency, 17%; and improvements in ICEV fuel economy, 14%.

3.3. Vehicle Primary Energy Consumption

3.3.1. Energy Efficiency of Conversion Processes Energy is used to recover a feedstock (such as crude oil), to transport the feedstock (e.g., via tanker or pipeline) to the end-user or fuel manufacturer, to refine the feedstock into a fuel, and to distribute the fuel to end users. The amount and kind of energy used at each of these stages depend on the feedstock and the final fuel; the method of recovery, transport, refining, and distribution; the efficiency of the various processes; the length of transport of feedstock and fuel, and many other factors.

As discussed above, we consider seven conversion processes. Here, we calculate the conversion efficiency of each stage for the seven conversion processes. Process energy use at each stage is calculated from recent EIA and U.S. Bureau of Census surveys of industries involved in various stages of a fuel cycle, and from other sources of process energy use.[47]

Figure 1 shows the resultant process efficiencies for the seven conversion processes, for 1995. Year 2010 efficiencies are the same, except for power plants, biomass liquefaction, and coal liquefaction (see notes to Figure 1).

Since the efficiencies of feedstock recovery and transportation are high (over 90%) and have not changed much over the last decade, we assume that these efficiencies will be the same in both 1995 and 2010. In contrast, we assume that the efficiency of coal liquefaction and biomass liquefaction will be improved from the current 60% to the 70% in 2010, because of the potential development of efficiency-improving technologies. Although the efficiency of petroleum refining is less than 90%, the efficiency may not be improved in the future because of diminishing crude quality, and because of demand for better refinery products. Therefore, we assumed the same petroleum-refinery efficiencies for 1995 and 2010. The efficiency of power plants depends on the type of fuel and the year. A detailed analysis of power plant efficiency is given in the following section.

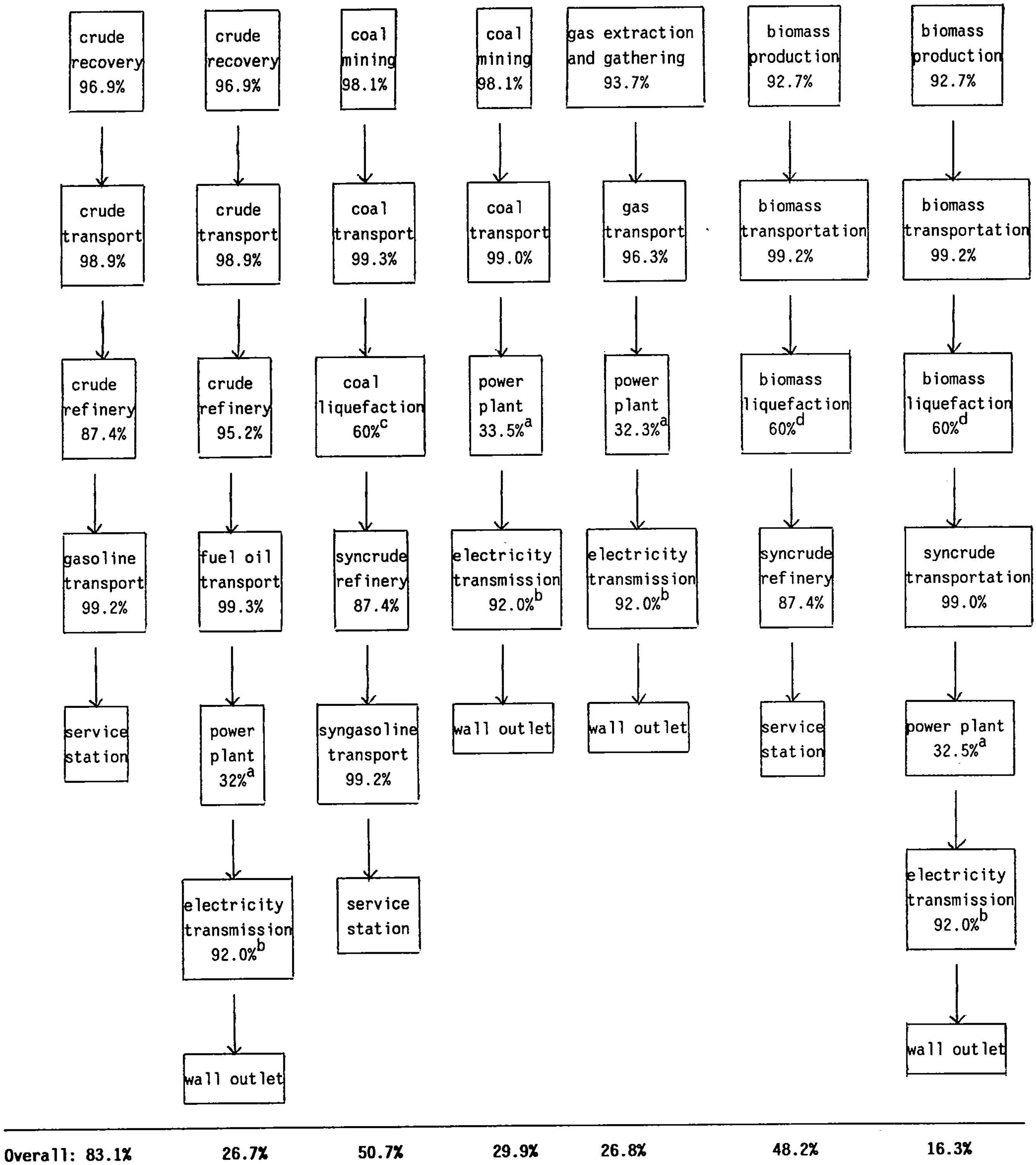

Fig. 1. Overall efficiency for seven energy-production processes, 1995

The data were calculated from DeLuchi,[48] except as noted. [a] Projected power plant efficiency in 1995. Year 2010 efficiencies are shown in Table 7. [b] From EIA.[17] [c] 60% for 1995, and 70% for 2010. From Salmon et al[48] and Lumpkin et al.[49] [d] 60% for 1995, and 70% for 2010. From Stevens.[50]

3.3.2. Power Plant Conversion Efficiency The conversion efficiency of an electric power plant is equal to mmBtu of electricity from the plant divided by mmBtu of fuel input to the plant. The heat rate, which is defined as fuel input requirement per unit of electricity output (Btu/Kwh), is often used to represent the conversion efficiency of fossil fuel plants.

The conversion efficiency of fossil-fuel plants increased from about 5% in the early 1900s to above 30% in 1960s.[51] Subsequently, there was little improvement in the efficiency, due to diminishing marginal returns on efficiency-improvement investments and the availability of inexpensive fossil fuels.[52] Efforts to improve power plant efficiency emerged after the world oil crises in 1973-74 and in 1979-80. However, the dramatic decrease in the world oil price in the 1980s slowed these efforts. An increase in energy prices in the future probably will rekindle these efforts.

Among the factors influencing power plant efficiency are the type and cost of combustion technology, the type and cost of fuel available, fuel quality, environmental regulations on power plants, the age of the plant, and operation and maintenance requirements. Some advanced technologies, such as combined-cycle combustion, are much more efficient than current technologies. Higher fuel prices in the future, together with the potential efficiency gains of advanced technologies, will eventually help these technologies be deployed. Poorer quality fuels will be used in power plants as better quality fuels become more expensive, and other things being equal, this can reduce plant efficiency. Power plant emission regulations also reduce plant efficiency. For example, scrubbers installed in coal plants for controlling SOx emissions consume 3-8% of plant electricity output.[53] Plant efficiency tends to deteriorate with age, but plant performance monitoring, improved instrumentation and testing, and application of retrofit technology can slow or even prevent efficiency deterioration.[52, 54]

The factors that determines plant efficiency are difficult to project, and thus it is difficult to predict the exact level of power plant efficiency in 1995 and 2010. In the following section, we examine the efficiency of existing power plants both with conventional technologies and with advanced technologies. We, then, project power plant efficiency in 1995 and 2010.

For the purpose of comparing energy consumption of EVs with that of ICEVs, the efficiency of the power plants which actually supply electricity to EVs--the marginal plants--should be considered. Although it has been claimed that EVs would be recharged during the night, using off-peak electric facilities, recharging in parking lots has been proposed to extend EV driving ranges, and quick recharging in central stations has been proposed to reduce recharging time. With these recharging options, EVs could be recharged during the day as well as at night. Even if only home recharging is available, without enough economic incentives, nighttime EV recharging cannot be ensured. Moreover, many different evening, night, and early morning recharging patterns are possible. Therefore, it is difficult to determine the marginal power plants. Rather than attempt to use the efficiency of marginal plants, we simply use the efficiency of average plants. Better understanding on future EV recharging patterns, electricity demand from other sectors, and electricity supply from electric utility systems will make it possible to identify the marginal plants.

We consider the following combustion technologies for each type of power plants: steam boiler and integrated gasification combined cycle (IGCC) for coal plants; steam boiler for oil plants; steam boiler and gas turbine (simple cycle and combined cycle) for gas plants; and gasifier steam-injected and combined cycles of gas turbine for biomass plants. IGCC is a clean-burning coal technology,[55-57] and therefore its share in future coal plants probably will increase due to stringent emission regulations on future coal plants enacted by the 1990 federal Clean Air Act.[58] The share of gas turbines will increase due to their low capital cost, low emissions, and high efficiency.[52, 59] The gasifier steam-injected gas-turbine technology has high conversion efficiency, low unit capital cost, and low emissions, which leads to low cost per KWh electricity generated, relative to direct combustion biomass plants.[60-61] We summarize heat rates and the corresponding conversion efficiencies for different types of plants in Table 6.

Table 6. Fossil fuel plant heat rate and conversion efficiency

Plant type and technology	Heat rate (Btu/Kwh)	Conversion efficiency(%)	Source
Power plants with current designs and combustion technologies			
Coal-fired plants:			
Conventional boiler	10,449-10,540[a]	32.4-32.7	Shipp et al[62]
Conventional boiler	9,900-9,960[b]	34.3-34.5	Makansi[54]
Conventional boiler	10,342[c]	33.0	Dowlatabadi et al[63]
Conventional boiler	10,300[d]	33.0	EIA[64]
Oil-fired plants:			
Conventional boiler	10,990[c]	31.0	Dowlatabadi et al[63]
Conventional boiler	11,011[d]	31.0	EIA[64]
Gas-fired plants:			
Gas turbine	10,883[e]	31.4	Dowlatabadi et al[63]
Conventional boiler	10,926[d]	31.2	EIA[64]
Power plants with advanced designs and combustion technologies			
Coal-fired plants:			
Not specified	9,000-9,600[f]	35.5-37.9	Touchton[65]
Combined-cycle	8,497-9,920	34.4-40.2	Touchton[65]
IGCC	9,000[g]	37.9	Spencer et al[57]
PFBC with combined-cycle[h]	7,755-8,124	42.0-44.0	Pillai[66]
IGCC[i]	7,616-8,066	42.3-44.8	Peters[67]
Gas-fired plants:			
Combined-cycle	8,480	40.2	Dowlatabadi et al[65]
Advanced combined-cycle	7,582	45.0	Williams et al[51]
Steam-injected gas turbine[j]	8,530	40.0	Williams et al[51]
Intercooled steam-injected gas turbine[k]	7,260	47.0	Williams et al[51]
Biomass-fired plants:			
Stem-injected gas turbine	8,980-10,498	32.5-38.0	Larson[60]

[a] The average heat rate of coal-fired plants in the East Kentucky Power Cooperative, Inc., which has eight coal-fired plants with a total capacity of 1,305 MW.

[b] The average heat rate of coal-fired plants in Tennessee Valley Authority (TVA) in 1981 and 1982, with a total capacity of 12,961 MW.

[c] The average heat rate of nine utility systems in the east of the U.S. with a total capacity of 82,409 MW of coal-fired plants and 22,370 MW of oil-fired plants.

[d] The average heat rate of the U.S. electric utility system. We used EIA's 1989 data on fuel input and electricity output for three types of plants (coal-fired, oil-fired, and gas-fired) to calculate these heat rates.

[e] The average heat rate of gas turbine systems in Michigan and New Jersey with a capacity of 2,041 MW of gas turbine units.

[f] The heat rate of the best coal-fired units projected for 1990.

[g] The projected heat rate of the IGCC system at the coal-fired facility in Cool Water, California.

[h] Pressurized fluidized bed combustion with the gas turbine/steam turbine combined cycle.

[i] IGCC system with slagging gasifier, Prenflo gasifier, and Texaco gasifier.

[j] Like the simple cogeneration cycle, except that steam not needed for heating is injected into the combustor to increase power output and electric efficiency.

[k] Like a steam-injected gas turbine with full steam injection, except with an intercooler between the compressor stages, which allows for operation at a much higher turbine inlet temperature.

The data in Table 6 show that coal-fired plants with current combustion technology achieve a conversion efficiency of 32.4-34.5%; oil-fired, 31%; and gas-fired, 31.2-31.4%. With advanced technology, coal-fired plants can achieve a conversion efficiency of 34.4-44.8%; gas-fired, 40.2-47%; and biomass-fired, 32.5-38.4%. In the long run, the use of advanced combustion technologies will increase power plant efficiency. In the short run, power plant efficiency can be improved through efficiency-improving programs.

Starting with the efficiency of current plants, the rate of addition of new capacity, the efficiency of new plants, and efficiency improvements to existing plants, we project average efficiency by type of power plants in 1995 and 2010. To project efficiencies in 1995, we assume that by 1995, the conversion efficiency of existing plants will increase by 0.5% over the current level for coal plants; and 1% for oil and gas plants. These efficiency improvements will be due to short-run improvement programs. We do not assume the addition of new plants between now and 1995. The lower assumed efficiency improvement for coal plants is caused in part by the efficiency penalty of stringent environmental regulations imposed on coal-fired plants by the 1990 Clean Air Act. The average of efficiency by type of power plants in 1995 is presented in Table 7.

To project the average efficiency in 2010, we assume that old generators are retired at an annual rate of 2.5% (based on an average 40-year life of a plant), and that electricity sales grow at an annual rate of 2.3%.[68] We assume that 1.5% out of the 2.3% increase in sales is satisfied by new capacity. To meet the 1.5% increase in electricity sales, the addition of new capacity for different types of plants will be different. The EIA projects that electricity sales from coal-fired plants will increase by 65% in the next 20 years; gas-fired plants by 131%; and oil-fired plants by negligible amount.[68] Considering the share of total electricity sales from each type of plants, we assume that electricity sales from coal-fired plants will increase by 1.3% per year between 1996 and 2010; gas-fired, 2.6%, and oil-fired, 0%. Therefore, to meet both the increase in electricity demand and the decrease in electricity supply due to the retirement of old generators, the capacity of new coal-fired plants will increase by 3.8% per year between 1996 and 2010; gas-fired, 5.1%; and oil-fired, 2.5%. We assume that the efficiency of 1995 existing plants will increase by 1.5% by 2010. We also assume the following efficiencies for the new plants built after 1995: 39% for coal and oil plants (we did not assume that all coal plants and oil plants would be combined-cycle), and 43% for gas plants (we assumed most of gas plants built would be combined cycle). With these assumptions, we calculate the average efficiency by power plant in 2010 (Table 7).

Because currently there are essentially no biomass-gasifier gas turbine facilities, we assume that the averaged efficiency of biomass-fired plants existing in 1995 and in 2010 will be close to the efficiency of new biomass-fired plants. We used 32.5% in 1995 and 38% in 2010 as the efficiency of biomass-fired plants.

Table 7. Projected power-plant conversion efficiencies (%)

Year	Coal plants	Oil plants	Gas plants	Biomass plants
1990	33.0	31.0	31.3	N/A
1995	33.5	32.0	32.3	32.5
2010	37.0	35.4	39.0	38.0

3.4. Petroleum Displacement by EVs

The transportation sector is completely dependent on petroleum-derived fuels, and is the largest petroleum-consuming sector in the U.S. economy. To reduce the vulnerability of the transportation sector and of the nation to disruptions in the world oil market, petroleum consumption in transportation must be reduced. EVs are potentially effective displacers of petroleum, because petroleum is a minor fuel input to electricity generation. This potential was recognized by the Electric and Hybrid Vehicle Act of 1976 which was designed to reduce U. S. dependence on imported petroleum.[69]

Below, we estimate per-mile petroleum displacement by EVs, by accounting for the use of oil to generate electricity and the use of petroleum products (gasoline, diesel, and residual oil) for the recovery, transportation, refining, and distribution of both power plant fuels and gasoline.

Table 8 presents the mix of fuels used to generate electricity. Nationwide, petroleum accounts for a small portion of fuel input, while coal accounts for over half of fuel input. Table 8 also shows the fuel mix of current electric systems in four major U.S. cities: Chicago, Houston, Los Angeles, and New York. We estimate petroleum displacement by EVs for the seven cases shown in Table 8.

Table 8. Percentage of electricity generated by different fuels

Region	U.S.			Chicago[d]	Houston[d]	Los Angeles[d]	New York[d]
Fuel mix case	1995[b]	2010[b]	1990 Marginal mix[c]	1990	1990	1990	1990
Coal	54.3	60.4	50.0	21.3	31.4	31.2	16.9
Petroleum	5.9	3.5	15.0	0.6	0.5	5.0	26.0
NG	12.3	14.1	30.0	0.4	56.4	34.1	14.5
Nuclear	17.7	14.0	2.0	77.7	11.7	24.5	39.3
Others[a]	9.8	8.0	3.0	0.0	0.0	5.2	3.3

[a] Includes hydropower, geothermal, petroleum coke, biomass, wood, waste, solar, and wind.

[b] Projected by U.S. EIA.[1]

[c] Marginal fuel mix of supplying electricity for EVs. Calculated by considering EV recharging patterns and electric capacity avalaibility. For details, see Deluchi.[47]

[d] Based on electricity generation from different fuels in the utility systems serving these cities. Electricity transactions among the utilities were also considered. For details, see DeLuchi.[47]

Petroleum consumption by EVs is due to two sources: the use of petroleum for electricity generation (shown in Table 8), and the use of petroleum products for processing fuels, e.g., coal, fuel oil, natural gas, and uranium, which are used for electric generation. While the estimate of the use of petroleum for electricity generation is straightforward, the estimate of the use of petroleum products as process energy for electric generation requires data on the amount of petroleum used in the whole fuel cycles for coal, fuel oil, natural gas, and uranium. Table 9 shows the amount of process energy used in the various fuel cycles, and the percentage of petroleum out of the total process energy consumption.

The formula for calculating EV petroleum consumption is

$$\begin{aligned} PC_{ev} = {} & EC \times 3412/(1-DL) \times [\sum_{i}(\%i \times PEU_i \times P\%PEU_i/CE_i) + \%Oil \\ & \times (1 + PEC_0 \times P\%PEC_0)/CE_0] \end{aligned} \qquad (2)$$

where PC_{ev} is the petroleum consumption of EVs in Btu per mile, EC is EV electricity consumption in Kwh per mile (from Table 5), 3412 is the conversion factor from Kwh to Btu, DL is the distribution loss of electricity from power plants to electric outlets (8%), %i is percent electricity generated from fuel i for an electric system (accounting all types of generation [from Table 8]), PEU_i is process energy use in Btu per Btu of fuel i input to power plants (from Table 9), $P\%PEU_i$ is the petroleum percent of process energy use for fuel i (from Table 9), CE_i is the conversion efficiency of power plants fueled by fuel i (from Table 7) (i = 1: coal; i = 2: NG; and i = 3: nuclear [or uranium]), %Oil is percent electricity generated from oil in an electricity system (from Table 8), PEU_0 is process energy use in Btu per Btu fuel oil input to power plants (from Table 9), $P\%PEU_0$ is the petroleum percent of process energy use for fuel oil (from Table 9), and CE_0 is the conversion efficiency of oil plants (from Table 7).

We did not consider use of petroleum products for biomass production and process and for biomass power plants, because biomass power plants are projected to account for very small percentage of total power plants in the U.S.

Table 9. Process energy use for one unit of energy output, and percentage of petroleum out of process energy use

Fuel cycle	Btu of process energy use per Btu of energy output[a]	Percent petroleum energy out of total energy use[b]
Crude oil to gasoline in service station	0.204	23.1
Crude oil to fuel oil in power plant	0.104	41.0
Coal to power plant	0.030	70.2
Field NG to power plant	0.109	1.9
Raw uranium to power plant	0.057[c]	10.0

[a] Process energy use is calculated as (1/process efficiency-1). The process efficiency was from data in Figure 1.

[b] From DeLuchi.[47] Different petroleum products (residual oil, diesel fuel, and gasoline) are used for energy recovery, transportation, conversion, and storage. Electricity, a portion of which is generated from oil, is also used for processing energy. We considered this use of petroleum products and electricity to estimate percent petroleum out of process energy use. We assume that 4.5% of electricity generation is from petroleum. Other second- and third-round uses of petroleum (e.g., oil used to refine crude oil to the energy products which are used for transporting coal) are not included.

[c] From DeLuchi.[47]

Similarly, petroleum consumption by gasoline ICEVs is due to two sources: vehicle gasoline consumption, and the use of petroleum-derived fuels (gasoline, diesel, and fuel oil) in the upstream parts of the fuel cycle (note that other energy sources [NG and electricity] are also used for the process).

The formula for calculating ICEV petroleum consumption in Btu per mile is

$$PC_{icev} = 125{,}000/MPG \times (1+PEU_g \times P\%PEU_g) \qquad (3)$$

where PC_{icev} is the petroleum consumption of gasoline ICEVs in Btu per mile, MPG is fuel economy of ICEVs (from Table 2), 125,000 is the heating value of gasoline in Btu per gallon, PEU_g is process energy use in Btu per Btu of gasoline output (from Table 9), and $P\%PEU_g$ is the percent process energy that is petroleum (from Table 9).

4. RESULTS

4.1. Primary Energy Consumption of ICEVs and EVs

The formula for calculating ICEV primary energy consumption is

$$PEC_{icev} = 125{,}000/MPG/PEE \qquad (4)$$

where PEC_{icev} is the primary energy consumption of ICEVs in Btu per mile, 125,000 is the heating value of gasoline in Btu per gallon, MPG is ICEV fuel economy (Table 2), and PEE is the process energy efficiency from primary source recovery to gasoline in service stations (Fig. 1).

The formula of calculating EV primary energy consumption is

$$PEC_{ev} = 3412 \times EC/PEE \qquad (5)$$

where PEC_{ev} is the primary energy consumption of EVs in Btu per mile, 3412 is the conversion factor from Kwh to Btu, EC is the electricity consumption of EVs in Kwh per mile (Table 5), and PEE is the process energy efficiency from primary source recovery to electricity in an electric outlet (Fig. 1).

Using Eqs. (4) and (5), and the data presented in previous sections, we calculate the primary energy consumption of ICEVs and EVs, and show the results in Table 10.

Table 10. Vehicle primary energy consumption (Btu per mile)
(by vehicle type, model-year, and primary energy source)

Vehicle type	Sub-compact car		Small van		Large van	
Year	1995	2010	1995	2010	1995	2010
Petroleum to gasoline: ICEV	5440	3979	7878	6526	10469	8672
Petroleum to electricity: EV	7036	3701	9850	5551	12665	6939
Change[a] (%)	29.3	-7.0	25.0	-14.9	21.0	-20.0
NG to electricity: EV	6999	3372	9798	5059	12598	6323
Change[b] (%)	28.7	-15.2	24.4	-22.5	20.3	-27.1
Biomass to gasoline: ICEV	9467	6352	13712	10417	18221	13843
Biomass to electricity: EV	11490	4901	16086	7351	20682	9189
Change[a] (%)	21.4	-22.8	17.3	-29.4	13.5	-33.6
Coal to gasoline: ICEV	8919	6524	12918	10700	17166	14218
Coal to electricity: EV	6270	3303	8777	4954	11285	6193
Change[a] (%)	-29.7	-49.4	-32.1	-53.7	-34.3	-56.4

[a] The percent change in primary energy consumption of EVs relative to that of ICEVs, when both use the same primary energy source. Calculated as [(energy consumption of EVs-energy consumption of ICEVs)/energy consumption of ICEVs]*100. A negative result means that EVs conserve primary energy.

[b] The percent change in energy consumption of EVs fueled by NG relative to the energy consumption of petroleum-fueled ICEVs.

The results of per-mile energy consumption presented in Table 10 indicate that in 1995, EVs consume 13-29% more primary energy than ICEVs if petroleum, NG, or biomass is used for both EVs and ICEVs, but that EVs consume 30-35% less coal than ICEVs if coal is used for both vehicles. In 2010, however, EVs consume less primary energy than ICEVs, regardless of types of primary energy sources. The reductions in EV energy consumption between 1995 and 2010 are due to reductions in per-mile EV electricity consumption and to increases in power plant conversion efficiencies. A sensitivity analysis on the ranges of these two parameters between 1995 and 2010 showed that reductions in EV electricity consumption contributed to about 85% of the reductions in EV primary energy consumption, and improvements in power plant conversion efficiency about 15%. This indicates that our results are very sensitive to EV electricity consumption, which, in turn, is determined mainly by EV battery technology and EV powertrain efficiency.

The energy consumption of EVs fueled by different fuels can be also compared with that of petroleum-fueled ICEVs. Using the results presented in Table 10, we calculate the primary energy consumption of EVs for the four primary sources, relative to primary energy consumption of petroleum-fueled ICEVs (Figs. 2 and 3). Fig. 2 shows that in 1995, EVs increase primary energy consumption by 8-30% (depending on type of vehicles), relative to petroleum consumption of ICEVs, if coal, petroleum, or NG is the primary source for EVs. The primary energy consumption of EVs will be the twice as high as that of petroleum-fueled ICEVs if biomass is the primary source for EVs. The high biomass consumption of EVs is due to low biomass liquefaction efficiency and low coversion efficiency of biomass-fueled power plants.

Figure 3 indicates that in 2010, EVs will reduce relative primary energy consumption by 7-20% (depending on type of vehicles) if petroleum is the primary source, 15-27% if NG is the primary source, and 17-29% if coal is the primary source. However, EVs will increase primary energy consumption by 6-23% if biomass is the primary source.

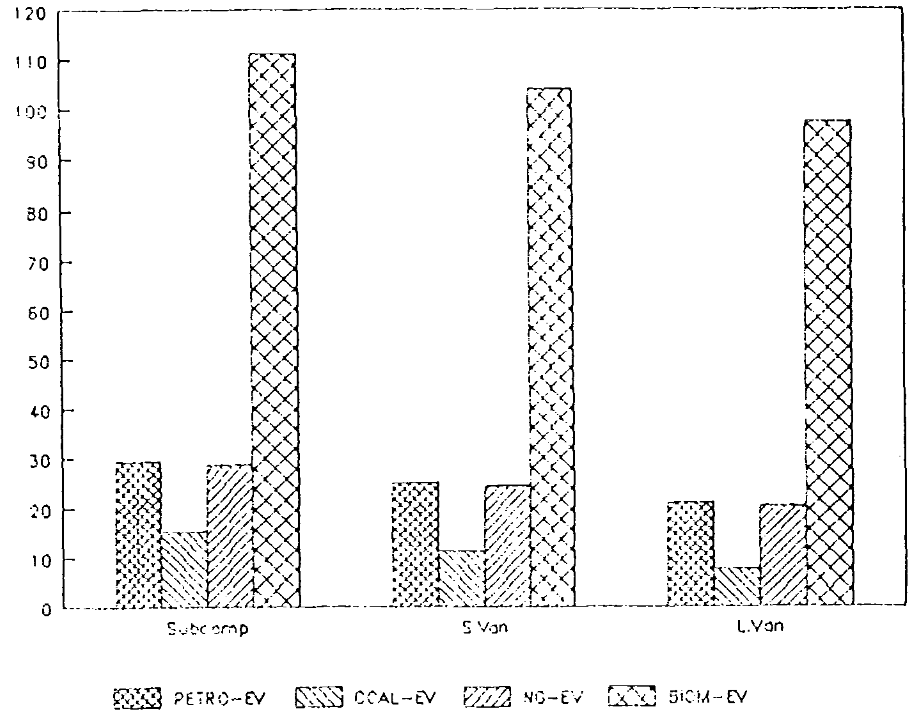

Fig. 2. The EV primary energy consumption relative to that of petroleum-fueled ICEVs (1995); PETRO=petroleum, BIOM=biomass.

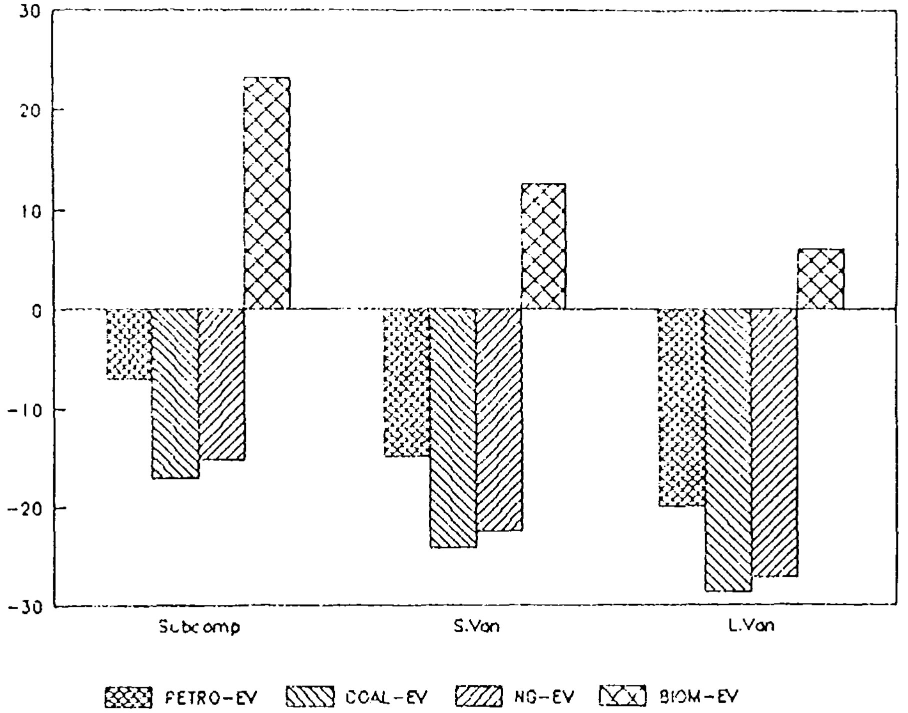

Fig. 3. The EV primary energy consumption relative to that of petroleum-fueled ICEVs (2010); PETRO=petroleum, BIOM=biomass.

4.2. Petroleum Displacement by EVs

The results of the EV petroleum displacement analysis are presented in Table 11. In many U.S. areas, EVs will reduce transportation petroleum use by over 90% in 1995 on a per-mile basis, and by over 95% in 2010. Thus, in most places EVs will reduce petroleum use almost in proportion to their VMT (vehicle miles traveled) penetration to the transportation sector. However, EVs will reduce petroleum use by 78% under the marginal fuel mix case, and by 63-65% in New York, both due to the higher use of oil-fired power.

Table 11. Petroleum consumption of ICEVs and EVs (Btu per mile)

Region		U.S.			Chicago	Houston	Los Angeles	New York
Electric Energy mix case[a]		1995	2010	1990 marginal mix	1990	1990	1990	1990
Sub-compact car:	ICEV[b]	4732	3462	4732	4732	4732	4732	4732
	EV[c]	496	166	1065	94	84	385	1765
	Savings(%)[d]	90.1	95.2	78.0	98.0	98.2	91.9	62.7
Small van:	ICEV	6854	5677	6854	6854	6854	6854	6854
	EV	656	250	1491	131	118	539	2471
	Savings(%)	90.4	95.6	78.3	98.1	98.3	92.1	64.0
Large van:	ICEV	9108	7544	9108	9108	9108	9108	9108
	EV	844	312	1917	169	152	693	3177
	Savings(%)	90.7	95.9	79.0	98.1	98.3	92.4	65.1

[a] For details, see Table 8.

[b] Petroleum consumption of ICEVs is calculated using Eq. 2.

[c] Petroleum consumption of EVs is calculated using Eq. 3.

[d] Percent petroleum savings by EVs relative to petroleum consumption of ICEVs, calculated as (petroleum consumption of ICEVs-petroleum consumption of EVs)/petroleum consumption of ICEVs x 100%.

The above analysis of EV primary energy savings and EV petroleum displacement has been conducted on a per-mile basis. The total energy savings and total petroleum displacement of EVs will be equal to per-mile results multiplied by VMT by EVs. Thus, large VMT by EVs will have large total regional energy impacts. However, caution must be taken in applying our per-mile results to a regional analysis, since we considered average power plants, not the marginal plants (although we do have a marginal fuel mix case in our analysis). If a large number of vehicles were electrified, substantial amounts of electricity would be needed. The large increase in electricity demand would likely change the plant mix and the energy mix of U.S. electric systems. Better understanding of the future fuel supply to electric systems and of EV recharging pattern will help identify the marginal plants which will supply electricity for EVs.

5. CONCLUSIONS

Per-mile primary energy savings impacts and petroleum displacement impacts of EVs are analyzed for three types of vehicles, for 1995 and 2010. Our analysis shows that advances in EV battery technology and improvements in EV powertrain efficiency are the main determinant of overall energy consumption by EVs, relative to ICEVs. If petroleum, NG, or biomass is used as the primary energy source for both ICEVs and EVs, EVs with current technology will increase energy consumption by 13-30%, depending on the type of primary sources and type of vehicles. However, more efficient EVs will reduce energy consumption by over 7-33%.

EV energy savings also depend on the type of primary energy sources used for EVs and ICEVs. If coal is used as the primary source for both EVs and ICEVs, EVs will reduce energy consumption in both 1995 and 2010 because of low efficiency of converting coal to syn-gasoline. If petroleum, natural gas, or biomass is used for both EVs and ICEVs, EVs may decrease or increase primary energy consumption, depending on advances in EV technology. EVs will substaintially reduce petroleum use per mile relative to petroleum consumption of petroleum-fueled ICEVs in many parts of the U.S. where electric power is and will be derived primarily from non-petroleum sources.

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