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A technology assessment and the external costs of selected transportation fuels

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Abstract

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Prices of fuels for vehicles do not account for environmental and other external costs, resulting in inefficiency in the energy market, a bias against new fuels and technologies that may have lower total costs to society, and a disincentive toward innovation in the industry. This thesis investigates the external costs of petroleum, compressed natural gas, battery-powered electricity, and fuel cells driven by solar-derived hydrogen, which are possible alternatives for fueling light-duty vehicles. As some alternatives are not yet available in the market, a technology assessment is also presented to determine the technological and economic obstacles to commercialization.

Although the results are preliminary, they indicate that among the alternatives, the external costs of gasoline are highest, and the lowest are for solar hydrogen fuel cells, which are furthest away from commercial availability. If externalities are accounted for, economic efficiency and environmental protection would be promoted, a "level playing field" created, and research and development for new technologies stimulated, allowing for least-cost transportation planning for society.

This thesis is dedicated to Wolfgang and Angelika. Wolfgang's support and love made it possible for me to pursue and complete my formal studies and Angelika's birth brought joy and inspiration, along with a renewed dedication to work for a world in which Partnership with the earth and with each other is possible.

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INTRODUCTION

The transportation sector currently accounts for one-fourth of all U.S. energy use and two-thirds of its petroleum consumption. Transportation is also the major contributor to air quality problems in urban areas. Motor vehicles, particularly cars and trucks, contribute close to half of all urban air pollution (Gordon 1991). Furthermore, without technological breakthroughs or other major changes in the way transportation fuel is used, negative environmental impacts are projected to increase, because of projected increases in the total miles traveled. In California, for example, total vehicle-miles traveled are forecast to grow 2% per year (Hwang and others 1994). Therefore, considerable effort is recently being expended in the search for cleaner fuels and new automobile technologies, particularly in California.

Economists have long argued that correct pricing is the key to market efficiency[1] and an optimal level of resource (e.g., fuel) consumption. Central in this debate is the assertion that energy prices do not reflect the true costs to society, that pollution and other forms of externalities[2] are not included in market prices, and that markets can efficiently determine fuel choices by incorporating external costs into the prices paid by consumers. In the case of personal transportation, in spite of pollution controls in the form of catalytic converters and cleaner gasoline, many urban areas across the country still do not meet federal quality standards, and the health costs that result from this pollution are not included in the gasoline price. Other forms of externalities related to petroleum and other fuels include noise pollution, water pollution, related aesthetic losses and increased national security costs.

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[1]Generally, economic efficiency means maximizing net benefits or minimizing net costs to society.

[2]An "externality" is the economic term used for the side effects of production or consumption which generate costs or benefits to society for which the producer (or the consumer) is not held responsible (Koplow 1993).

According to many economists and analysts, this market failure can be resolved by the incentive/disincentive method of price adjustment due to the unaccounted-for costs that are imposed on society as a result of the use of a particular fuel or technology. By estimating and accounting for these costs in the price of fuels, manufacturers, the government, and consumers can make choices as efficiently as possible, at the same time allowing market forces to prevail.[3] For transportation planning, estimates of external costs together with private costs would offer a more complete picture for effective decision-making, which is particularly important when we are faced with several alternatives for automobile fuels, as early advantages may "lock in" a technology via structural requirements even though the technology may not be best choice in the long term or have the lowest total, or social, cost.

This work reviews and synthesizes recent studies of the external costs of petroleum and compares them to the costs estimated for three alternative "fuels": battery-powered electricity from current generation technologies, compressed natural gas, and solar energy-derived hydrogen for fuel cells. These fuels are chosen for this work because they are perceived to have the possibility for more than just incremental environmental benefits over petroleum.

Most alternative fuels and technologies, however, are not commercially ready. Therefore, the technologies that are necessary for compressed natural gas, battery-powered electric, and hydrogen fuel-cell powered vehicles to become available in the market will be investigated. The first section of this thesis will summarize the current status of these technologies and address the technological and economic barriers to commercialization. The second section will review and estimate the external costs of petroleum and the three alternatives.

Before proceeding, though, a short explanation will be given for the stages that new technologies normally go through before they are mass-marketed and made available

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[3]Sometimes, the polluter may be over-regulated, not in the *amount* of pollution reductions called for, but in the *manner* that those reductions must be obtained (mandated pollution reduction strategies as well as the government agencies that oversee them may also be inefficient) (Koplow 1993).

to the general public, as this will aid in understanding the technology assessment. The distinctions to take note of are "concept" car, "prototype" car, and commercially-available car, as the models that will be mentioned in this thesis will roughly belong to one of those three categories.

A concept vehicle is usually in the early stages of development. Research has been done, and, according to expert opinion and theoretical calculations, the engineering idea has possibility for success. Sometimes a model is built, using some components that have specifications close to the final goal, and some that do not. Usually, the concept is revolutionary in some way, and it is believed that it can become reality in the foreseeable future.

Prototypes are usually further along in development. A model is made with real components that work. Like concept vehicles, prototypes are custom-built. What is still needed is a way to manufacture the product so that it will be cost-effective. Manufacturing a new component or product is not always straight-forward, and it usually is expensive at first. Sometimes the final mass-produced product will not look exactly like (or function exactly like) the prototype from which it was modeled, often because manufacturing finds it too difficult to meet the original specifications.

A commercially-available vehicle is already likely to be mass-produced, with components that are "off the shelf," and it is usually widely available. Although it is difficult to say how long each stage takes, it is important to know what stage in its development a product is in, because a product in the concept stage is usually significantly further away from reality than one being considered for manufacturing.

A technology assessment of the three new vehicle "fuel" technologies follows, beginning with battery-powered electric vehicles.

PART I. TECHNOLOGY ASSESSMENT

CHAPTER I

Status of Battery-Powered Electric Vehicles

Unknown to most people, battery-powered electric vehicles, with a typical range of about 50 miles, dominated the automobile market in the 1890s (MacKenzie 1994). In 1977, Japan had 13,000 electric vehicles (EVs) and England about 30,000, mostly in use as delivery vehicles (MacKenzie 1994). Today, most major auto manufacturers have already developed modern battery-powered concept or prototype vehicles, and some have placed a limited number of such vehicles into fleet service for demonstration purposes (Washington State Energy Office (WSEO) 1993a). Small, specialty companies have also converted vans, pickups, and passenger cars to run on battery power, and some are currently working on building EVs from the "ground-up."

One reason for this rise in recent activity in the electric vehicle market is California's 1990 Low-Emission Vehicle (LEV) statute, which is a sales mandate that is also being considered for adoption by several other states. The California Air Resources Board wrote the LEV program to help clean up California's urban air basins, which have been out of compliance with federal air pollution standards for a significant number of days each year. Compared to gasoline-powered vehicles, EVs can produce large reductions in CO and hydrocarbon emissions, and they may have benefits in NO_x and CO_2 as well (Hwang 1993; MacKenzie 1994; Reizenman 1993).

The LEV statute mandates, among other things, that at least 2% of all vehicles sold in California in 1998 be zero-emission vehicles. The percentages will increase to 5% by 2001 and 10% by 2003 (Woodruff, Armstrong, and Carey 1994; International Energy Agency (IEA) 1993; Organization for Economic Cooperation and Development (OECD) 1993). Given that time limitation, zero-emission vehicles (ZEVs) are limited to battery-powered electric vehicles.

Electric vehicles, however, need additional development work before they are commercially viable. Most important is increasing the energy density and lifetime, and reducing the cost and weight of batteries (MacKenzie 1994; Russell 1991; DeLuchi, Wang, and Sperling 1989). Lead-acid and nickel-cadmium are the only commercially available batteries at the present time. Nickel-cadmium batteries are too expensive and not sufficiently durable for applications in automobiles. Lead-acid batteries, while popular for current use, do not have a high enough energy density, which limits the vehicle range from about 50 to 60 miles for converted vehicles (WSEO 1993a) to about 100 to 120 miles for streamlined, "built-from-the-ground-up" prototypes such as the "Impact" (Russell 1991; Hwang 1993; WSEO 1993a). General Motors had plans to market the Impact, a long-range (100+ mile), 75 mph top-speed subcompact, but plans were delayed, presumably because of concerns that the public would not buy the vehicle because of its $25,000 price. From a consumer's perspective, the current drawbacks to electric vehicles are the limited range, the higher initial purchase price, battery replacement costs that stem from the relatively short life span of current batteries, and the long recharging times. All of these drawbacks link directly to battery technology.

The successful development of advanced electric vehicles thus depends primarily on the commercialization of advanced battery technologies that are now under development. An assessment of promising battery technologies follows.

Battery Technologies

Battery technologies currently being developed for electric vehicles include advanced lead-acid, nickel-cadmium, nickel-iron, sodium-sulfur, and nickel-metal-hydride. Other possibilities for batteries include lithium-type and metal-air technologies, but these are currently only in the very early stages of development and will probably not be available until sometime after the year 2000 (IEA 1993).

Currently available lead-acid batteries have reasonable cost, energy densities of between 37 and 42 Wh/kg, and lifetimes exceeding 500 charging cycles (WSEO 1993a; IEA 1993; MacKenzie 1994). Lead-acid batteries also have the advantages of relatively abundant materials, years of experience, and a well-developed servicing and recycling infrastructure. (The batteries are similar to conventional auto batteries). However, they are heavy for the amount of propulsion that they deliver. For example, to power the 2200 pound GM Impact for 120 miles would require about 870 pounds of lead-acid batteries, which is about 40% of the total weight of the vehicle! Another negative is that lead-acid batteries have reduced performance in cold climates, as they experience reduced and less efficient charging at temperatures significantly below room temperature.

Advanced lead-acid batteries offer improved design over currently available lead-acid batteries. Advanced lead-acid batteries are expected to have energy densities of 45 Wh/kg and to be maintenance-free, and they are projected to last about 80,000 miles, or about 900 cycles (MacKenzie 1994). These attributes, however, have yet to be proven in long-term field testing.

Sodium-sulfur batteries are emerging as a promising mid-term technology because of their high energy densities, low maintenance, long service life, abundant materials, and low material costs. However, sodium-sulfur batteries must be kept at temperatures of 300ºC to 350ºC between uses, which requires insulated double-walled vacuum containers, and built-in heaters to remelt the sodium and sulfur when necessary (MacKenzie 1994; IEA 1993). DeLuchi, Wang and Sperling (1989) state that this type of insulation would maintain battery temperature for about 2 weeks. After sitting idle for more than two weeks, however, the auxiliary heating would be required. Except for this heating requirement, the battery is maintenance free. For the sodium-sulfur battery, energy densities have been shown to be as high as 110 Wh/kg (WSEO 1993a), with 80-90 Wh/kg to be more typical (Reizenman 1993; DeLuchi, Wang, and Sperling 1989). While the remaining technical problems are challenging (extending battery life and finding lighter insulation), they require improvements in manufacturing processes and do not appear to require technical breakthroughs.

Nickel-cadmium batteries are already in use in some Japanese and European EVs. They offer a higher energy density than lead-acid batteries, but are more expensive (approximately 5 times that of lead-acid batteries) because both the nickel and the cadmium are costly (IEA 1993). Current useful life is also a question, with numbers in the literature ranging from only 300 cycles (WSEO 1993a) to over 1000 cycles (MacKenzie 1994; IEA 1993). Furthermore, cadmium is a highly toxic material, so its use would need to be carefully controlled. A new technology for recycling nickel would also need to be developed so that it could be reused in batteries.

Nickel-iron batteries are lighter and more powerful than lead-acid batteries, with energy density and cycle life similar to nickel-cadmium batteries (IEA 1993). Most researchers believe that the nickel-iron battery may be the most likely near-term successor to the conventional lead-acid battery (DeLuchi, Wang, and Sperling 1989). However, Ni-

Fe batteries are costly (again because of the nickel in them), and may require regular maintenance.

Nickel-metal hydride batteries look promising because they offer more than twice the energy density of lead-acid batteries and a three-to-one advantage in the volumetric energy density (MacKenzie 1994). According to the manufacturer, current batteries have achieved an energy density of 80 Wh/kg, and battery life is expected to reach 2000 to 3000 cycles. Using these batteries in GM's Impact would increase the car's range to 300 miles, and they could probably last as long as the car (MacKenzie 1994). Another possible plus is that energy densities of around 150 Wh/kg are believed to be attainable. The manufacturer also claims that they are environmentally "friendly" and 100% recyclable. However, nickel cannot be recycled and reused as a battery material using currently available recycling technology (IEA 1993), so this claim would need to be verified. To help achieve commercialization, the U.S. Advanced Battery Consortium awarded a cost-sharing contract with the manufacturer in 1992 (MacKenzie 1994; WSEO 1993a).

Other batteries that are not as developed include zinc-bromine, nickel-zinc, sodium-nickel chloride, lithium-iron sulfide, lithium polymer, and metal-air. These are expected to be available around the year 2000 or shortly thereafter (IEA 1993). It is difficult to say which of these or any other technologies will eventually be the most desirable. For some of the batteries described above, commercialization does not depend on major technical breakthroughs. What is still needed, though, is continued progress in manufacturing and quality control, and a closer investigation into the environmental impacts of the manufacturing, use, and recycling of these batteries.

Electric Vehicle System

The power system in an electric vehicle includes the battery, the power electronics, the electric motor, the connection to the wheels, and the controls. In the past 15 years, these technologies have been maturing, and remaining engineering work is considered straightforward compared to the work remaining for batteries. Repairing EVs should also be more straightforward. Because there are fewer moving parts than in an internal combustion engine and a simpler power train, EVs are likely to have lower maintenance and repair costs than their gasoline counterparts: there would be no oil and muffler to replace, and no fluid systems to maintain. Also, EVs should tend to last longer. For example, electric milk vans in Britain reportedly last three times as long as comparable internal combustion engine vans powered by gasoline (DeLuchi, Wang, and Sperling 1989).

For calculating the energy efficiency of the total system, today's electric motors are about 90% efficient, batteries are about 75% to 80% efficient, and battery chargers about 90% to 92% efficient (Pratt 1992; OECD 1993; WSEO 1993a). With an average of 33% power plant efficiency (fossil fuel plants) and a 97% transmission efficiency, the energy efficiency from power plant to electric-vehicle propulsion is just over 20%. For a coal-fired power plant, factoring in efficiencies for coal mining (98.1 %) and coal transportation (99.3%) (IEA 1993) would bring the overall energy efficiency to about 20%. For natural gas-fired generation, the efficiency for gas extraction and gathering is 93.7% and for gas transportation, 96.3% (IEA 1993). Factoring these in would give an overall energy efficiency of just over 18.7%. The overall energy efficiency for the electric vehicle would depend on the fuel mix used to generate electricity to recharge batteries, but it would likely be between 18.7% and 20%. In contrast, according to the U.S. Department of Energy, current internal combustion automobiles fueled on petroleum have an overall energy efficiency of about 11%. This figure includes crude oil refining through vehicle propulsion (U.S. Department of Energy 1992). Factoring in the energy efficiency for crude oil recovery of 96.9% (IEA 1993) not included in the DOE figure would bring the overall petroleum pathway efficiency to just over 10.5%. Note that these figures do not include heating, air conditioning, and other auxiliary energy requirements. While petroleum-fueled vehicles would have an advantage in that waste heat could be used to heat the automobile, electric vehicles would have an advantage in urban and stop-and-go traffic, as there would be no wasteful idling. Air conditioning would affect both types of vehicles' overall energy requirements per mile traveled, as would higher payloads and steep hills, of course.

A study conducted by the California Air Resources Board showed that the urban energy consumption of a converted Geo Metro is about 63% that of a gasoline Metro (which is already an efficient gasoline-powered vehicle) (Pratt 1992), which is consistent with the relative efficiencies indicated above, given that the converted Metro is probably not optimized for efficiency. Pratt states that this study took into account the energy consumption "from the oil well to the road" for both electric and gasoline vehicles. Further studies like Pratt's are needed to verify results and to investigate efficiencies as technologies become more optimized. For example, the Impact's electric motor is claimed to be about 95% efficient, and its regenerative braking system allows the motor to generate electricity during deceleration, returning energy to the batteries (Nadis and MacKenzie 1993). All of the characteristics and differences between electric and gasoline vehicles need to be carefully investigated for a thorough comparison of these technologies.

While electric vehicle pathway efficiencies may look attractive, it is important to remember that EVs ultimately yield only about 60 to 120 miles per charge on presently available batteries, and that each charge currently takes about six to eight hours. Furthermore, the range for EVs is reduced by factors such as higher payloads, steep hills, cold temperatures, and auxiliary system use, which includes the air conditioner, heater, and radio. The heating and air conditioning system, for example, can use up to about 25% of the battery's power, reducing the range proportionally (Russell 1991). Innovative solutions to this auxiliary energy requirement appear feasible. For example, work is being done on using photovoltaic power to cool the inside of the car while it's in the sun, so that the cooling load is reduced. Photovoltaic electricity may also serve another function, as a recent study by the Jet Propulsion Laboratory showed that having PV cells slowly recharge batteries could slow down battery degradation by reducing the depth of discharge and could significantly extend, perhaps even quadruple, their life (Russell 1991; WSEO 1993a). Other factors that can increase range include streamlined designs, reduced vehicle weight, regenerative braking, and improved tires. Improved design is why the GM Impact requires only about 0.11 kWh/mile (70 Wh/km) during normal operation (Reizenman 1993), as compared to about 0.2 to 0.5 kWh/mile for other light-duty EVs (MacKenzie 1994). To meet peak power requirements during steep climbing or fast acceleration, secondary energy storage devices such as ultracapacitors and flywheels are also being investigated. Finally, EVs may not be suitable for very cold climates unless the problems with battery performance and the high auxiliary load requirement for interior heating can be successfully resolved.

While EVs may not suit the general automobile market until battery performance is increased, they look promising for certain niche markets where the lower range is not a problem. Since large amounts of emissions are produced by a gasoline-powered car in the first few minutes, EVs can look pretty good for urban areas with huge air quality problems.

The following is a summary list of current advantages and disadvantages of battery-powered electric vehicles as compared to gasoline-powered vehicles:

Advantages:

- Smoother, quieter, faster response vehicle
- Greater reliability and less time in a repair or maintenance shop
- Can recharge at home instead of at gas stations
- Emission control devices not required. Also no periodic emission checks
- No idling
- No danger of fire in crashes. Perceived to be safer

Disadvantages:

- Reduced driving range
- Probably reduced storage space
- Higher initial purchase price
- Longer recharging time
- Batteries may need to be replaced
- May not be suitable for cold climates

Benefits to Society:

- Air quality benefits at point-of-use. Overall air quality benefits are also expected in many areas
- Substantially reduced use of imported petroleum

Costs to Society:

- Some research and development costs for batteries if government contributes to their development

CHAPTER II

Status of Natural Gas Vehicles

Around 1988, over 507,000 natural gas vehicles (NGVs) were in use world-wide (WSEO 1993). At that time, there were about 30,000 light duty natural gas vehicles operating in the U.S. (WSEO 1993b; Hirshberg and Scullary 1992). Today, that number is close to 50,000. The majority of natural gas vehicles operated in the U.S. today are converted vehicles, and they are typically used in fleet service. Several companies currently offer conversion kits, with conversions ranging in price from $3000 to $4500 per vehicle. Recently, though, major automobile manufacturers have begun to offer dual-fuel and some dedicated natural gas vehicles (Seisler 1993). Most of these are vans and light duty trucks, with currently three models of automobiles. Thus, one can say that dedicated-fuel compressed natural gas light duty vehicles are already commercially available. The automobiles that are offered at the time of this writing are still bi-fuel (gasoline and compressed natural gas) though.

There appear to be no major technology issues that will prevent the continued wider availability of natural gas vehicles. However, there is a hesitancy to further expansion on the part of both automobile manufacturers and natural gas fuel retailers, because of a problem in the industry called "the chicken and the egg" syndrome. This occurs when fuel retailers want to make sure there will be plenty of natural gas vehicles available before they commit to compressed natural gas refueling stations, and where manufacturers will avoid making a commitment to building NGVs unless refueling stations are available, which explains the greater availability of dual-fuel vehicles compared to dedicated models. Currently, most NGVs are in service in larger fleets which are centrally refueled, such as those owned by utilities, rather than being owned by consumers. That may be changing soon, however, as refueling stations with public access are being added. Currently, there are about 35 natural gas refueling stations located in Pacific Gas and Electric (PG&E) territory in California and an additional 35 are planned over the next couple of years, about half of which will have full public access (PG&E 1993).

Dedicated natural gas vehicles have a shorter range than gasoline-powered vehicles, about 200 miles. That is because of the lower energy density per unit volume of a gas compared to a liquid fuel. Natural gas is stored on-board vehicles in heavy and a gas compared to a liquid fuel. Natural gas is stored on-board vehicles in heavy and bulky gas storage cylinders which are made of either high-strength steel, composite steel, aluminum, composite wrapped aluminum, or composite carbon fibers with a thermoplastic inner liner (WSEO 1993b). Typical gas storage pressures range from 2,400 psi to 3,000 psi. For these pressures, commercially available storage cylinders already exist. Furthermore, the cylinders have a proven safety record. In vehicle accidents, they have demonstrated to be safer than gasoline tanks and have resulted in significantly smaller rates of injury and fire (WSEO 1993b). Although there is a lack of sufficient in-use data on toxicity, fire, and other safety issues to produce meaningful statistical results, expert opinion projects that compressed natural gas is certainly no more dangerous than gasoline as a vehicle fuel (EPA 1990). Experience in other countries and preliminary studies seem to indicate that the injury rate for CNG vehicles was significantly lower than for U.S. vehicles as a whole and fewer fires were attributed to the CNG fuel system and vehicles (EPA 1990). Another survey states that although both types of vehicles have similar accident rates, the injury and death rate is much lower for CNG-powered vehicles (Baker, Draves, and Klausmeier 1992). There is some concern over the greater risk of physical injury to the operator of a CNG refueling system when the equipment fails. Injuries such as cryogenic burns from the rapidly-expanding gas and strikes by a flailing hose could result. However, both of these risks could be minimized by proper equipment design (EPA 1990). Additional experience is required, though, to confirm these preliminary judgments.

NGVs also emit less air pollutants than their gasoline counterparts. While NO_x emissions probably would be the same, CO, hydrocarbons, and particulate emissions would be significantly reduced.

Finally, natural gas supplies appear ample. Recent studies found that earlier assessments systematically underestimated reserves, and that total U.S. resources are now estimated to be 1,000 to 1,300 trillion cubic feet. That should last the U.S. about 60 years at the current rate of use (Flavin 1992).

The following is a summary list of advantages and disadvantages of natural gas-powered vehicles as compared to gasoline-powered vehicles:

Advantages:

- Lower fuel costs
- Clean burning operation with reduced maintenance and extended engine life
- Perceived to be safer

Disadvantages:

- Conversion costs are high
- Costs for manufactured NGVs are somewhat higher because of low production numbers
- Reduced range
- Lack of sufficient public access refueling stations

Benefits to Society:

- Reduced air emissions
- Reduced pollution in refining, processing and transportation compared with petroleum. Also, contamination of soils and groundwater, and oil spills are eliminated
- Reduced consumption of petroleum, of which up to half is imported
- More secure fuel supply

CHAPTER III

Status of Hydrogen Fuel Cell Vehicles

According to several analysts, recent breakthroughs in fuel cell technology will allow the hydrogen fuel cell-powered vehicle, with further development, to emerge as a fleet vehicle within about a decade. A fuel-cell powered vehicle, fueled on hydrogen derived from electrolysis is that is driven by renewable energy seems like an environmentalist's dream. Emissions from the fuel cell vehicle would be reduced to zero, and other environmental impacts are likely to be insignificant. Also, because fuel cell vehicles will allow much faster refueling and a longer range than battery-powered electric vehicles (BPEVs is used here to distinguish them from fuel cell vehicles, which are also run on electric power), they may likely be more attractive to the consumer.

Although hydrogen can also be used to fuel internal combustion engines, this technology will not be discussed here, since the technology of interest is fuel cell vehicles. This is because vehicles powered by fuel cells are between two and three times more energy efficient than those powered by internal combustion engines. Some analysts predict that fuel cell vehicles will be available sooner, because this efficiency advantage translates directly into a cost advantage. If that is the case, the internal combustion engine fueled by hydrogen may not be developed for commercial use.

The technologies that need further development for the successful introduction of fuel cell electric vehicles run on solar electricity-produced hydrogen are: the fuel cell, technologies for storing hydrogen onboard the vehicle, the fuel cell vehicle as a functioning system, and photovoltaic electricity. Although electrolysis is a commercially available technology, further engineering work would need to be done in order to make it compatible with the intermittent nature of solar electricity. The technology assessment will begin with a discussion on fuel cells.

Fuel Cells

A fuel cell is an energy conversion device that transforms fuel directly to electricity without combustion. The oxidation reaction involves the release of chemical energy through the transfer of electrons. When the electrons travel through an external circuit, useful work is done. In a fuel cell, hydrogen from a storage system and oxygen from air, for example, react electrochemically to produce pollution-free electricity, water, and waste heat, eliminating the intermediate step of combustion. During operation, no fuel cell component is consumed, and the fuel cell is able to produce electricity as long as the reactants are provided.

Although the basic principles of fuel cells have been known since 1839, it was not until their development for the Apollo lunar and space-shuttle missions that they emerged as a possible technology for the generation of power (MacKenzie 1994). In a fuel cell vehicle (FCV), a fuel cell powers an electric motor, which is part of an electric drive train similar to that used in battery-powered electric vehicles. Like a battery, a fuel cell has no moving parts and is more energy efficient than an internal combustion engine. The operating efficiencies have been shown to be between 50% and 65%, and vehicle system efficiencies are expected to surpass 50% (U.S. Department of Energy 1993a; 1993b; MacKenzie 1994). Miller and Swan (1994) state that the fuel cells themselves have efficiencies between 45% and 70%, depending on the power output, and system efficiencies run about 45% to 50%. As an example, the recently-built Ballard fuel cell bus demonstrated system efficiencies between 38% and 46%, depending on how it was being driven. This is encouraging, as this experimental fuel cell bus was not yet optimized for efficiency (Miller, personal communication, June 1994).

Unlike a battery, though, which stores electrochemical energy, fuel cells can operate as long as the chemical reactants are present. Furthermore, because fuel cell vehicles exhibit the best features of EVs (high efficiency, zero emissions, low noise, and a long life) together with the best features of gasoline-powered vehicles (fast refueling and a longer range), they could potentially be used in a larger share of the market than battery-powered electric vehicles.

Within the last year, a Ballard fuel cell bus and an Energy Partners Green Car (a fuel cell car) were publicly demonstrated (Miller and Swan 1994), and Daimler Benz is working on building a fuel cell car that will have power characteristics for more typical driving by 1996 (Miller, personal communication, June 1994; Williams 1994). Ballard is planning several stages of a program that is expected to lead to commercialization of fuel cell buses by 1998 (Miller and Swan 1994).

These and other recent advances have increased interest in fuel cells for transportation and have significantly shortened expected times for the commercialization of light duty fuel cell vehicles. Analysts are now predicting that fuel cell vehicles can be available for demonstrations in fleets shortly after the year 2000 (U.S. Department of Energy 1993b; Ogden and Nitsch 1993). Miller expects fuel cell cars to follow buses by three to five years (Miller, personal communication, June 1994). However, to realize the many benefits of fuel cells for commercial applications, further development work needs to be done. The size and weight of current fuel cell designs need to be reduced for personal automobiles, a greater load-carrying capability (power density) is needed, and the system cost needs to be reduced and/or the system performance improved (U.S. Department of Energy 1993b).

Several fuel cell technologies most promising for transportation applications are currently being investigated: phosphoric acid fuel cells (PAFCs), alkaline fuel cells (AFCs), solid oxide fuel cells (SOFCs), and proton exchange membrane (PEM) fuel cells. PAFCs so far have low current- and power-densities, slow startup, high costs, and excessive weight to be used in light-duty vehicle applications. AFCs, although the oldest fuel cell technology, currently require pure hydrogen and pure oxygen free of carbon dioxide for their use. SOFCs, in the early stage of development, require very high operating temperatures, about 1000ºC (MacKenzie 1994). Out of the four technologies, many analysts consider the PEM fuel cell to be the most attractive for light-duty vehicles in the near term (Williams 1994; Miller and Swan 1994; DeLuchi 1992; Ogden and Nitsch 1993), and this technology is currently being supported and developed by the DOE (U.S. Department of Energy 1993a; 1993b).

PEM fuel cells are promising to be both compact and inexpensive, and they have a potential for long life and low maintenance. The ion-conducting electrolyte is a thin polymer membrane. The electrodes are thin sheets of a porous, conductive material (carbon), coated with a platinum catalyst. A single membrane/electrode assembly is less than a millimeter thick, with a stack consisting of many such assemblies connected in series. A typical vehicle would need a fuel cell stack weighing about 125 pounds and occupying an equivalent volume of about 20 to 25 gallons (Williams 1994).

Platinum is the only scarce material required for PEM fuel cells. Fortunately, recent advances in research have reduced the platinum requirements by a factor of 40, down to about 3.6 grams per vehicle, which would translate to a cost of about $40 more than what is already used in conventional catalytic converters (Williams 1993). The only other costly material in a PEM fuel cell is the membrane electrolyte, for the reason that it is not yet a commercial product. However, in the polymer industry, as quantities demanded go up, costs generally decline rapidly. Because the manufacture of these membranes requires processes that are similar to a wide variety of other polymer membranes (Williams 1993), it seems reasonable to expect that the membrane material will follow a similar cost path. The materials in the PEM fuel cell other than the platinum catalyst and the membrane are relatively common and should be inexpensive (Williams 1994).

Despite the significant recent advances in PEM fuel cells, further development needs to be done to increase the power-density and decrease the size and bulk of the fuel cell.[4] To reduce the power requirements of a fuel cell system, engineers are investigating other energy storage devices--ultracapacitors, batteries, and flywheels--which will boost the power when going uphill or passing. For the present time, fuel cell power densities (hence the fuel cell's bulk) are best suited for buses. With a few years of development work though, we may be seeing light-duty fuel cell vehicles on the road, especially if advances are also made in storing hydrogen. The focus will now turn to storage technologies.

Storage Technologies

The storage of a sufficient amount of hydrogen fuel to get a long enough range without too much space being used for the storage system is another technical challenge. Some analysts consider lightweight, high energy density storage of hydrogen as perhaps the greatest technical challenge for fuel cell vehicles (Ogden and Nitsch 1993; Robinson and Handrock 1994). Commercially available gas-storage systems are heavier and bulkier than those for liquid fuels such as gasoline, and they do not deliver the typical 350 to 400 mile range of a gasoline-powered vehicle.

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[4]The power available to the system is directly proportional to the volume of the fuel cell, while the energy is a function of the amount of hydrogen stored.

Hydrogen can be stored on-board a vehicle in many forms, using different technologies. It can be stored as a gas in a high pressure tank, as a low temperature liquid in a specially insulated container, as a powder in metal hydride tanks, adsorbed to active carbon at low temperatures, and in liquid chemical carriers. None of these options, though, offer the simplicity, the lighiness, and the energy compactness (and therefore the range) of a gasoline storage system.

Liquid hydrogen may seem to be a feasible way to store hydrogen compactly. However, hydrogen gas liquefies at a temperature of -253ºC, so it would require a highly insulated (and therefore bulky) vacuum container. Further, liquefying the hydrogen requires between 30% and 60% of the energy of the hydrogen fuel, increasing costs significantly (MacKenzie 1994; Robinson and Handrock 1994; U.S. Department of Energy 1992). A certain percentage of fuel, about 2% to 5%, would evaporate each day. And during refueling, additional hydrogen would boil off. Also, the losses are inversely related to the tank size, so light-duty vehicles would evaporate the higher percentages. There are, therefore, significant disadvantages in using liquid hydrogen in vehicles.

Metal hydride storage tanks contain powdered metals that store hydrogen at about the same volume density of liquid hydrogen storage tanks. Disadvantages include great weight, a long refill time of 20 to 30 minutes, high cost, and complex water and heat management systems (MacKenzie 1994; DeLuchi 1992). Unless these issues are resolved, metal hydrides may not be the technology of choice.

Carbon-adsorption storage systems are still in the research stage. Here, hydrogen is put into refrigerated, activated carbon tanks that are similar to compressed gas tanks. The activated carbon in the tanks allows the energy density to approach that of liquid hydrogen, which is about 4 wt %, and additional improvements are possible (U.S. Department of Energy 1992). This technology may be the option of choice for the future if improvements continue.

Storing hydrogen as a compressed gas seems to be the preferred method at the moment (Williams 1994; DeLuchi 1992). To get a 250 mile range in a light-duty fuel cell vehicle, a 35 to 40 gallon composite-material canister, weighing about 180 pounds, and pressurized at 500 atmospheres (7350 psi), would be needed (Williams 1994). The DOE's estimates show that for a pressure of 6000 psi and a 1.7 cubic feet storage system volume

(12.7 gallons), the range would be about 91 miles (U.S. Department of Energy 1992). Correspondingly, a 40 gallon container would yield a range of 286 miles. Naturally, the range would depend very much on the characteristics of the fuel cell vehicle, such as vehicle design and weight, and the efficiency of the fuel cell system. As a check one can calculate, from the energy content of the stored hydrogen and the given range, the energy required per mile of travel and compare this figure to the energy consumed per mile for battery powered electric vehicles. Using DeLuchi's figure of 3.28 MJ/liter energy content for a hydrogen fuel system energy density at 6000 psi, the energy delivered to the fuel cell is 0.48 kWh/mile. DOE's energy density at 6000 psi is about 70 kBTU/ft^3. The energy delivered here is 0.38 kWh/mile. As hydrogen gas and oxygen from the air are converted to electricity at a system efficiency of about 50%, the per-mile efficiencies are within the range of typical compact battery powered electric vehicles, which is what would be expected.

The DOE's long-range goals, however, are to achieve weight and volume storage densities comparable to gasoline (U.S. Department of Energy 1992). These goals may be optimistic and also unnecessary for fuel cell vehicles to become commercialized. According to unpublished survey data from researchers at the University of California at Davis, the minimum acceptable range for an "all purpose vehicle," as distinct from a special purpose urban vehicle, is about 400 kilometers, or about 250 miles (DeLuchi 1992). DeLuchi (1992) claims that if the storage pressure were increased to 8000 psi instead of the more typical 3000 psi, compressed gas storage would be attractive compared with the other storage technologies discussed. (Perhaps 6000 psi would be sufficient, as the numbers in the previous paragraph seem to indicate.) The technical obstacles to the refueling equipment and the storage vessels also seem not to be insurmountable, according to DeLuchi. Carbon-fiber wrapped aluminum vessels would be required, and the recent drop in carbon fiber costs make this option more economical than it used to be. The "ideal" pressure, however, would depend on the tradeoffs between the cost of the storage system, the energy efficiency of compression and cost of compression, and the range desired.

Hydrogen from Electrolysis using Photovoltaic Electricity

Hydrogen can be produced and used on a global scale from a variety of renewable energy sources (wind-, solar-, and hydro-electricity, which drive the process of electrolysis) and by gasification of biomass. Until these renewable energy sources are more economical for wide-scale use, hydrogen can be produced least expensively from steam reformation of natural gas. It is also possible to produce hydrogen from the gasification of coal. The technology of interest for the future, though, is the production of hydrogen through photovoltaic electrolysis, because of the possible environmental advantages.

Electrolysis splits water into its constituent elements hydrogen and oxygen when a direct current is passed through an electrolyte (often a solution of potassium hydroxide in water). Electrolysis technology is well established and commercially available. Engineering work, however, still needs to be done in designing electrolysis technologies that will tolerate variable operation, which would be the case with photovoltaic electricity. Preliminary work with photovoltaic electrolysis so far has shown no intractable difficulties. Additional work on the long term performance and reliability of intermittent electrolysis systems will be helpful in establishing this technology.

Electrolysis is currently 70% to 75% efficient. With further improvements, it is possible for efficiencies to go up to 85% to 90% (Ogden and Nitsch 1993; Ogden and DeLuchi 1992). The maximum theoretical value, based on thermodynamic limits, is 94% (U.S. Department of Energy 1992).

The increasing efficiencies of thin film amorphous-silicon (α-Si) solar cell technologies is generating excitement for the use of photovoltaic electricity as a power source for electrolysis. The efficiency of the first α-Si solar cells was only about 1%. In 1991, the best α-Si cells achieved stabilized efficiencies of about 10% (Carlson and Wagner 1993; Kelly 1993). Efficiencies of 18% have been achieved in the laboratory. After 2005, stabilized efficiencies of at least 18% are expected for multi-junction α-Si cells (Carlson and Wagner 1993).

Thin films of amorphous silicon offer the significant advantages of reduced raw materials and great reductions in processing and energy costs compared with crystalline solar cells. Low cost, high-volume manufacturing is also anticipated for thin-film technologies. However, this has yet to be demonstrated, as large manufacturing facilities have not yet been built. As efficiencies continue to increase, though, mass-production will become more attractive, making low cost electricity from photovoltaic cells possible.

Thin-film polycrystalline solar cells are also promising, with costs for electricity expected to be under $0.06 per kWh by the first decade of the 21st century (Zweibel and Barnett 1993). However, it is important to realize that these cost projections cannot automatically be counted on. On the contrary, one needs to be particularly wary of cost estimates because of the unforeseen factors that can affect costs. For example, nuclear power was once predicted to be "too cheap to meter" (Brower 1990), which is probably one reason why studies done in the 1970s estimating electricity costs for the 1990s were about two to three times off their mark. Uncertainties exist, as is true for any emerging technology. Nevertheless, costs have been coming down rapidly and are likely to continue to do so, and a big plus is that development in photovoltaics will continue regardless of the hydrogen industry's stake in it because of its attractiveness to other applications.

Some analysts claim that less than 0.1% of U.S. land area would be needed to supply the entire U.S. fleet of automobiles and light trucks with photovoltaic-produced hydrogen (about 4.8 exajoules per year) for fuel cell power at the level of driving projected for 2010 (Williams 1994; Ogden and Nitsch 1993). For this scenario, a PV system efficiency of 15% is assumed, with a electrolyzer efficiency of 80%.[5] The 4.8 EJ is calculated from the year 2010 light-duty vehicle transportation energy projection of 14.4 EJ divided by three (because of the three-fold greater efficiency of fuel cell systems compared with the internal combustion engine). However, the analysts seem not to have considered the overall efficiency of hydrogen in this pathway, specifically the storage efficiencies of hydrogen. Because of efficiency losses in the bulk storage and onboard

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[5]For a PV system efficiency of 10% (more typical of what can be achieved today), an 80% electrolyzer efficiency, and solar incidence data from the China Lake/Las Vegas areas, the area of the U.S. that would be required would be less than 0.13%, assuming also that the area needed would be double the solar array area.

storage of hydrogen which are both 75% efficient according to the DOE (U.S. Department of Energy 1992), a greater proportion of land area will be needed. After factoring in the storage efficiencies, the estimated PV land area will need to be almost doubled (about 1.8 times), for a final figure of about 0.18% of the total U.S. land area, which is about 6480 square miles. However, the DOE's figures of 75% efficiency for both bulk storage and also for onboard storage may need to be verified, as these introduce significant losses into the pathway if the efficiencies are indeed that low. The storage efficiencies are determined by the energy efficiency of compressing the hydrogen to storage pressures and any gas losses that may occur during bulk storage, refueling, and use. Since analysts claim that the efficiency for the compression of hydrogen to standard storage pressures is in the 90s (OECD 1993; DeLuchi, personal communication, June 1994), as it is for the compression of natural gas, the hydrogen pathway efficiency needs to be further investigated before any conclusions can be drawn.

Hydrogen Fuel Cell Vehicle System

Hydrogen in a fuel cell vehicle can be used with an efficiency that is about three times that of gasoline in an internal combustion engine[6] (ICE) (Williams 1993; Ogden and Nitsch 1993). Although efficiencies for current internal combustion engines are only about 15%, efficiencies for the fuel cell are about 50%, as shown previously.

Fuel cell powered vehicles could use electric controllers and drive trains that are similar to those used in battery-powered electric vehicles. Compared to an internal combustion engine, an electric drive would provide a higher torque at the lower speeds of which most driving consists. There would also be less lag in the response of the motor, making the fuel cell vehicle, as the BPEV, more fun to drive. For high power requirements, a booster power source, such as a small battery, a flywheel, or an ultracapacitor, can be integrated into the system. However, the application of a fuel cell to meet the dynamic load needs of the electric drive is still a complex engineering problem. There has been little experience so far in the engineering of a fuel cell power system to

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[6]For clarity, if methanol was used as the fuel, the efficiency would be 2-1/2 times that of an ICE. These numbers are not always distinguished in the literature.

meet dynamic driving demands (Miller and Swan 1994). Daimler-Benz has the most ambitious goals for building a fully functioning, light-duty fuel cell vehicle with sufficient power for typical driving. It plans to build such a car by 1996 (Miller, personal communication, June 1994).

Although market costs are not investigated in this work, the literature states that fuel cell vehicles would cost little more than gasoline-powered internal combustion vehicles in mass production. It is true that estimating the future costs of purchasing and operating a hydrogen FCV is very speculative, as assumptions must be made about the costs and performance of technologies that are currently only prototypes or research projects. Still, in many of the possible scenarios that DeLuchi (1992) considers, hydrogen FCVs would have a lower lifecycle cost than gasoline vehicles, and in almost all scenarios, a lower cost than battery-powered electric vehicles and hydrogen ICE vehicles.

The following is a summary list of advantages and disadvantages of hydrogen fuel cell electric vehicles (when the hydrogen fuel is derived from solar electricity-powered electrolysis) as compared to gasoline-powered vehicles:

Advantages:

- Instant acceleration response
- Reduced time in a repair shop
- No pollution control inspections
- Instant start-up under any conditions
- No idling

Disadvantages:

- Possibly a bit less power than gasoline vehicles
- Probably a shorter range
- Probably less storage space

Benefits to society:

- Almost no emissions of greenhouse gases
- No emissions of CO, hydrocarbons, particulate matter, NO_x, SO_x, or other toxic pollutants
- No use of imported petroleum

- No water or land pollution associated with petroleum extraction, refining, distribution, and use

Efficiency Comparison of FCVs with BPEVs

In this thesis, we assume that fuel cell vehicles will be refueled with solar-derived hydrogen and battery-powered vehicles will be recharged using near-term conventional generation technologies. However, BPEVs could conceivably be recharged using solar electricity as well. If electricity from photovoltaics is assumed to be the original source of energy for both vehicles, a comparison can be made on how efficiently this energy is used for vehicle propulsion. In other words, on a relative basis, assuming comparable vehicle weights, how much will one unit of solar electricity yield?

For BPEVs, as stated before, the transmission of electricity (from central stations) is 97% efficient, battery chargers are 90% efficient, batteries are 80% and the electric motor drive, 90%. The total efficiency from PV electricity to vehicle propulsion is 63%. This means that one unit of solar electricity will yield 0.63 units of propulsion for a BPEV.

For FCVs, solar electricity would drive the electrolysis process (about 80% efficient), the hydrogen gas would be stored in bulk (75%), transmitted by pipeline (97%), stored onboard the vehicle (75%), and then used in the fuel cell and motor drive system (50%) for vehicle propulsion. Using these numbers, the total efficiency would be 22%. If higher efficiencies are assumed for storage (say, 90%) and for electrolysis (85%), the total efficiency is 33%. This means that one unit of solar electricity would yield between 0.22 and 0.33 units of propulsion for a FCV.

Hence, BPEVs will probably use electricity at least twice as efficiently as FCVs, because of fewer losses in the pathway, making them more attractive from the standpoint of energy use. However, other advantages and disadvantages come into play, as is discussed above.

Now that a technology assessment of the alternative automobile fuels and associated technologies has been presented, the focus will be on analyzing the external costs of petroleum and the three alternative fuels. A technology assessment and an analysis of external costs will prove enormously helpful in planning a transportation future that is least cost to society.

PART II. EVALUATION OF EXTERNAL COST STUDIES

CHAPTER IV

Background

The external costs of automotive fuels include the costs related to the negative consequences of air, water, and land pollution, the risks of global warming, dependence on foreign oil, and other similar environmental and social effects. Although these external effects are not accounted for in the price of fuel, society pays for these damages in indirect ways, such as in the reduced health of its citizenry, in the loss of environmental amenities such as clean water for recreational and drinking purposes, in the loss of ecosystem health and biodiversity, in lower agricultural productivity, and even in more direct economic losses, such as higher personal and business taxes. In short, there is a reduction in the quality of life that is not acknowledged or accounted for, and this decline affects current and future generations. And although the air pollution emitted per vehicle per mile, for example, has been reduced through the use of required pollution control devices and other measures, the ultimate objective is to minimize the sum of the private costs and the external costs. By estimating and accounting for externalities in the price of economic transactions, decisions regarding personal transportation choices can be made more responsibly and resources can be used more efficiently.

The process of identifying and valuating externalities consists of five phases or steps. In the first step, the pollution or emissions sources and the quantities and types of pollutants are determined. Step number two requires knowledge of the dispersal of these pollutants. Next, the populations exposed to the pollutants are identified. These populations could be either humans, animals, plants, buildings, or anything else that could incur damage from pollutants. The fourth step attempts to identify the responses of the exposed populations to the pollutants. These responses can be thought of as the environmental impacts or damages. Finally, the last phase requires the estimation of the cost of these impacts or damages. Often, the cost of the statistically expected outcome, which is the risk of damage, rather than the actual damage itself, is estimated (Pace University 1991). This is especially true when environmental costing is performed for the purpose of resource planning, for instance, for utility resource planning, or for transportation planning.

The economic value of the environmental risks or damages can ultimately be thought of as the amount that society would be willing to pay to avoid the risk (willingness to pay, or WTP) or the amount society would require as compensation to accept the risk voluntarily (willingness to accept, or WTA). Several methods can be used to determine these WTP or WTA economic values. The methods depend on whether market prices for these damages exist or can be derived, or whether credible prices cannot be easily determined. Environmental damage to food crops, for example, can be more easily valuated because market prices for food crops exist. For damages where market prices do not exist, the valuation process is tricky. For example, the value of the risk of early death to a "statistical human life" is not clear. On the contrary, considerable controversy over the costs of some of the effects can exist. Furthermore, the process involves the placing of monetary values on certain populations or effects, which is controversial in itself.

For those risks of damage where economic valuation is not straightforward, several techniques are used to approximate values. These valuation techniques include the accounting method, which approximates the expenditures required to remedy or mitigate the damages; the revealed preference method,[7] which is based on observing consumer behavior; the contingent valuation method, which relies on surveys for obtaining values that certain people put on various amenities; and the awards method, which derives costs from jury awards.

In spite of these and other creative methods, some environmental risks may seem impossible to valuate for various reasons, including the fact that the occurrence of certain events can be highly uncertain. In this case, analysts may come up with a range of costs which correspond to a range of possible outcomes when the occurrence of certain events is unclear. Examples of many kinds of these risks will be encountered in later chapters.

The external costs of four alternative automobile fuels: gasoline, electric power from batteries, compressed natural gas, and solar hydrogen for fuel cells, in that order, will

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[7]A subset of this method is the hedonic pricing method, which looks at actual housing prices to determine the value of certain amenities such as the degree of visibility or the presence of a scenic view.

now be studied. The purpose is to attempt an external cost comparison of the alternatives, so that the results can be used for choices and decisions regarding fuel pricing and transportation planning. This is accomplished by a critical review and synthesis of the most recent comprehensive external cost studies for the alternative fuels. One chapter is devoted to each of the four alternative fuels, starting with petroleum.

The external cost studies summarized here use U.S. national data for analysis when available. When not, local data are used for extrapolation to the national level when appropriate.

CHAPTER V

External Costs of Petroleum-Fueled Vehicles

The MacKenzie, Dower, and Chen, and the Miller and Moffet Studies

The social cost studies reviewed for petroleum-fueled vehicles are The Going Rate: What it Really Costs to Drive, authored by James J. MacKenzie, Roger C. Dower, and Donald D. T. Chen (1992) and The Price of Mobility: Uncovering the Hidden Costs of Transportation, authored by Peter Miller and John Moffet (1993). In The Going Rate, MacKenzie, Dower, and Chen assert that the private motor vehicle is deeply subsidized in this country, which leads to an increase in undesirable consequences such as air pollution and ill health, risks to the global environment, risks to our energy security, and congested traffic. Using the "polluter pays" principle, the authors calculate the external costs and the indirect costs of operating private motor vehicles, including indirect market costs (such as the cost of road maintenance) and propose policy recommendations. In The Price of Mobility, Peter Miller and John Moffet estimate and compare total costs for personal motor vehicles, buses, and trains. Miller and Moffet state that their report is the first attempt to estimate full costs for these three modes of transportation. Although several studies exist that estimate auto-related air-pollution costs, many are simply outdated, and they do not estimate other external costs (Miller and Moffet 1993).

Both the MacKenzie, Dower, and Chen, and the Miller and Moffet studies are based on aggregate national data, so the results are appropriate at the national level. However, because these studies do not focus on estimation of the external costs of the operation of petroleum-fueled light-duty motor vehicles as compared with alternatively-fueled light-duty motor vehicles, which is the intent of this work, they are not exactly ideal. Also, The Going Rate includes all private motor vehicles, including heavy-duty trucks and diesel-fueled vehicles, while The Price of Mobility addresses passenger cars and other light-duty vehicles, such as light trucks and vans. Therefore, they cannot be compared exactly. One must multiply the estimates derived in The Going Rate by about 50% to better compare the two studies, as about half of the damages due to highway vehicles can be assigned to gasoline-powered passenger cars (DeLuchi, Sperling, & Johnston 1987). As we will see, even multiplying by this factor does not yield estimates that can be easily compared, because the same effects were not estimated, and light-duty trucks are not included in the 50% factor. Still, these studies are currently the most recent and thorough available, so the relevant information for this work can be extracted from their studies. Nevertheless, these studies should not be taken as more than a "starting-point" for future research, as there is considerable uncertainty in many of the research studies from which the estimates are derived, a scarcity of studies which attempt to estimate certain externalities, and a lack of sufficient studies to draw hard conclusions. It is likely, though, that the external costs presented here are low, because of externalities that have not been included.

The external costs that MacKenzie, Dower, and Chen study include air pollution costs, global warming costs, energy security costs, congestion, motor vehicle accidents, noise, vibration damages, and land loss costs. Miller and Moffet analyze these and subsidies to oil companies, water pollution, damage to historic properties, loss in property values, and urban sprawl costs. Note: The studies will be referred to as the "MacKenzie" study and the "Miller" study from this point on in the text.

Several of the categories of externalities mentioned above arise independent of the alternative fuel used. Because this is an intramodal study focusing on light-duty vehicles, they will only briefly be mentioned here, as these externalities would apply equally to all light-duty vehicles regardless of the characteristics of the fuel or the technology. For example, the building of roads for vehicles would result in land loss and the loss of wetlands, and the movement of these vehicles would result in congestion and vibration. Vibration caused by motor vehicles, in turn, would lead to damages in buildings and other man-made structures. It is important, however, to note that the total external costs derived for the various technologies in this study are by no means complete, because the costs that apply equally to all will not be included.

Also included in MacKenzie's and Miller's analyses are the "socialized" market costs that cover road construction and maintenance, highway services, and parking that are not fully covered by user fees and are partially shifted on taxpayers. Because these costs are related to the use of the vehicle itself and are unlikely to vary significantly whether the automobile is battery-powered, gasoline-powered, or fuel-cell powered, these costs will also not be included here. For example, the weights of the different vehicles (e.g. electric car vs. gasoline-powered car) probably will not vary significantly and therefore will not make a noticeable difference to road damage, especially since cars and light trucks do not cause the great majority of the damage. However, it is important to note that gasoline taxes and other user fees usually do not fully cover road construction, maintenance, and services, and that a significant portion of these costs are paid by taxpayers and local property owners, according to both MacKenzie's and Miller's analyses. In fact, some necessary services such as road repairs are postponed to the future, increasing the highway cost burden for future generations. Further discussion of this shifting of costs is beyond the scope of this analysis. The estimation of the various external costs will now be reviewed, beginning with the externalities that are essentially equal across the different fuels and technologies.

Land Loss and Loss of Wetlands

The construction of roads and highways has contributed to the loss of wetlands, watershed regions, groundwater recharge areas, parklands, scenic areas, historic and cultural areas, and agricultural land. Wetlands provide important ecological services, including floodpeak reduction, groundwater recharge, water quality improvement through natural filtering processes, food and habitat for fish and wildlife, and shoreline stabilization (Miller and Moffet 1993). And according to some estimates, almost half the land in a typical American city is used to accommodate motor vehicles (MacKenzie, Dower, and Chen 1992). Road construction can also affect historic buildings and archaeological properties. To make room for new roadway, these may either be destroyed or mitigation efforts taken. Also, the construction of new roads and highways can affect existing neighborhood property values either positively or adversely, depending on various factors. MacKenzie states that although the costs of land loss are partially reflected in the costs of land purchased for road construction, the true social costs would have to consider the full environmental and historical values, and these have not been estimated. These costs are equal in an intramodal analysis and will not be considered further.

Damages to Buildings and Man-Made Structures

Vibration from motor vehicles can deteriorate buildings and monuments. This is especially true for the vibration that is caused when heavy vehicles (especially heavy-duty trucks) hit potholes. Nearby buildings, monuments, as well as underground pipes can be continuously stressed and eventually damaged, and vibration can also cause stress and fatigue in the occupants (MacKenzie, Dower, and Chen 1992). MacKenzie cites a study that states that heavy vehicles (tractor trailers and buses) are responsible for most of the damage, and that heavy-duty vehicles are responsible for 95% of all damages to roadways and bridges as well. Because the light-duty vehicles analyzed here will not have significant differences in weight to affect these damages, the vibration externality is ignored.

Congestion Effects

Perhaps the most complained-about external cost associated with the use of motor vehicles for personal transportation is the congestion that causes delay, an increase in accidents, and stress. Congestion intensifies environmental impacts, increases commuting times, raises vehicles' operating expenses, lowers worker productivity (due to stress and fatigue), boosts insurance costs, and slows the delivery of business products. The toll of congestion to the health and mental well-being of drivers is also notable, as congestion is believed to increase blood pressure, frustration, and aggressive driving habits (MacKenzie, Dower, and Chen 1992). And according to the Federal Highway Administration (FHWA) congestion is rapidly worsening. Although both MacKenzie and Miller discuss congestion in their studies, only a part of congestion costs are borne strictly by third parties. However, one as a driver can impose costs on other drivers by one's presence. Because the costs associated with congestion would be independent of the type of fuel used, regardless of whether they are considered external or not, this cost will not be discussed further.

Accidents

Both MacKenzie and Miller cite studies that estimate the costs of motor vehicle accidents not borne directly by drivers (but rather by pedestrians and bicyclists). Regardless of the actual externality cost in this case, the rate of accidents involving vehicle collisions will probably be minimally influenced by the type of fuel and automobile technology, as all types of vehicles could be equally safe. Therefore, these costs will not be included in this analysis. It is assumed here that accidents due to explosion of fuel tanks or fire are also equally likely to occur, given earlier assessments that the alternative fuels are as safe or safer than petroleum. This assumption can be confirmed once experience with the various technologies accumulates.

Noise

Motor vehicles contribute significantly to unwanted urban noise. Sources of noise caused by driving include tires, engine exhaust, engine and related equipment operation, brake friction, air brake operation, transmission and drive train friction, horns, theft alarms, and construction and maintenance-related noise (Miller and Moffet 1993). Some of the effects of noise include reduced productivity due to work disruptions and impaired performance, reduced property values, stress, irritability, insomnia, fatigue, and even temporary or permanent hearing loss in extreme cases. Costs include health care costs to remedy the effects mentioned, economic costs, and noise reduction and attenuation costs.

Noise externalities will be neglected for the purpose of this analysis, which is to distinguish the differences between the fuels studied. There are two main reasons why the noise factors between the alternative technologies can be considered minimal: one is that although, for example, an electric car is considered quieter than a gasoline-powered car, light-duty vehicles cause only a small percentage of the total noise. The biggest noise polluters are trucks, which are responsible for about 85% of the unwanted noise (MacKenzie, Dower, and Chen 1992). The second reason is that the operation of the engine and the engine exhaust is only one source of noise, and that road friction, break operation, horns, and alarms contribute significantly to the total noise. One study cited in Miller's analysis claims that engine exhaust noise contributes only about 10-15% to the overall automotive noise and another suggests that most noise results from road friction, not from vehicle engines. The difference, then, between an electric vehicle and a gasoline-powered one may not be as significant as one might think, for the reasons specified. Further studies could be done, however, to confirm this assertion.

The following externalities may reveal significant differences depending on the characteristics of the fuel and technology. These external costs will be included in the external cost aggregation, and they are the basis on which the different fuels will be compared.

Air Pollution Damages

Air pollution caused by motor vehicles damages human health, crops, trees, other ornamental vegetation, buildings and structural materials, and it reduces visibility. Health effects on humans from direct automobile emissions and ozone include eye, nose and throat irritations, coughs, impaired breathing, headaches, chest tightness, reduced concentration, reduced capacity for activity, and even death (Miller and Moffet 1993). In addition, air pollutants have synergistic effects which can further increase the threat to health, not only to humans but also to animals and vegetation.

In the United States, transportation is responsible for about 40 to 60% of the ozone precursor emissions of NO_x and hydrocarbons; 70 to 80% of CO emissions; 85% of benzene pollution; 4% of SO_x; 14% of particulates; and about one third of all CO_2 emissions (Miller and Moffet 1993). In some urban areas, the proportions attributable to transportation are even higher. For example, in Los Angeles mobile sources are responsible for 96% of CO, 72% of NO_x, and 52% of VOC emissions, according to literature cited by Miller. Since about 98% of the energy used in transportation comes from petroleum (Sperling and DeLuchi 1989), these pollutants are ascribed directly to the production and use of petroleum in motor vehicles.

For external costs due to air pollution, MacKenzie cites a study conducted by researchers at the University of California, Davis (DeLuchi, Sperling and Johnston 1987). In this study, damages caused by motor vehicle air pollution are estimated to be between $10 billion and $200 billion per year (in 1989 dollars). These damages include illnesses and premature death in humans, reduced agricultural productivity, damage to structural materials, reduced visibility, and others. In his evaluation of the study, MacKenzie states that the large variation in the estimates depends mostly on the uncertainty in the number of deaths and illnesses caused by vehicle-related air pollution and the lack of agreement on the value of human health and life. To be conservative, MacKenzie uses the lower estimate of $10 billion for his external cost aggregation. MacKenzie's external cost aggregation is shown in Table 1.

TABLE 1

MACKENZIE -- ANNUAL EXTERNAL COSTS ($ BILLIONS)

Air Pollution	10
Global Warming	27
Security Costs	25.3
Total	62.3

Examination of the U.C. Davis study (DeLuchi, Sperling, and Johnston 1987) shows that the estimates of both the number of early deaths due to air pollution and the value placed on a human life, obtained by the authors from the review of several earlier research studies, vary as much as one order of magnitude. The product, therefore, can vary over two orders of magnitude. To reduce this range somewhat, DeLuchi, Sperling, and Johnston take into account such factors as the age and geographic location of the study and the relative air quality at the time, the assumptions made by the studies (e.g. whether the dose-response function, also called the damage function, is assumed linear, what pollutants are included, what statistical assumptions are made, etc.), and the consistency of the studies. Moreover, by choosing "plausible upper and lower values," they come up with a range that spreads over slightly more than one order of magnitude. The estimate for the number of excess deaths attributable to air pollution chosen is between 50,000 and 120,000 for 1985. And the value of a life, chosen from their literature review, ranges between $500,000 and $5,000,000.[8] Factoring these together with the estimate that highway vehicles are responsible for between 15 to 25% of the damage (this range also resulting from review of several studies), the authors arrive at a

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[8]These figures are typically derived from willingness-to-pay economic studies such as the safety belt method and the occupational wages method. Most of the more recent studies arrive at figures that range from $1.0 million to $3.4 million (Tregarthen 1990).

range of $3.75 billion to $150 billion for the external cost of human mortality due to air pollution in 1985. In a similar fashion, the authors come up with an estimate for morbidity, which is $3.75 billion to $31.25 billion per year (in 1985 dollars).

DeLuchi, Sperling and Johnston, for the same year, estimate the damages to agricultural crops, most of which are reported to be caused by tropospheric ozone. By using several studies that estimate pollutant and ozone damages to crops, a couple of which were national, and also by taking into account the studies' ages and other factors, the authors estimate oxidant damages to agricultural crops between $2 billion and $8 billion per year. They also assume an equal amount for damages to all other vegetation. Damages to animals and wildlife were not estimated.

Damages to materials are arrived at by reviewing research studies that estimate, for example, the value of damages that would be reduced if air quality standards were met. The estimates from several studies are rather consistent with one another, after DeLuchi, Sperling, and Johnston take into account the average emissions and the value of materials in the year of each study, the geographic range of each study, and the pollutants considered, including the degree of pollution reduction assumed. By tossing out the high-end of one study's estimates, the authors arrive at a range of $5 billion to $20 billion per year for all damage to materials from air pollution in 1985.

Using several "willingness to pay" studies to determine the value of the damage to visibility, the reviewers estimate $10 billion to $35 billion per year for 1985. The visibility damage, materials damage, and the vegetation damage estimates are also multiplied by the range of 15 to 25%, to account for the percentage of the total damage responsible by highway vehicles. The total of all the five types of damages, mortality, morbidity, vegetation, materials, and visibility, is then further reduced by a factor of 12.5% which takes into account "substitution effects." This factor takes into account the possible overestimation of the total when independent estimates of the components are added together, because "some of the components are at least partial substitutes for one another." DeLuchi, Sperling, and Johnston arrive at the final total of $9 billion to $174 billion per year for air pollution damages caused by highway vehicles for the year 1985. By factoring in a discount rate of about 3% per year, MacKenzie arrives at the estimate of $10 billion to $200 billion for the year 1989. He then uses the low-end estimate for his external cost aggregation, which would make his estimate probably excessively conservative.

Miller estimates air pollution costs for petroleum-fueled light-duty vehicles that are based on several recent reports on the external costs of electricity generation. He uses values for the damage cost per gram of various pollutants derived from these studies (a couple of which are evaluated later on in this work) and sets up a range of values ($ per gram) for each pollutant. Thus, he assumes that the cost per gram of a pollutant is the same regardless of whether it is emitted by power plants or by automobiles. The pollutants included are CH_4, CO, NO_x, SO_x, particulates, N_2O, VOCs, CFCs, and CO_2. Miller admits that although these studies represent the most recent, comprehensive, and reliable air pollution cost estimates, they probably underestimate transportation pollution effects as electric generation plants disperse pollutants through high stacks and are often located in remote areas. In particular, the effects of motor vehicles in crowded urban areas are probably considerably underestimated.

Another complication in Miller's analysis is that no single report from which he derives his $/gram values gives estimates for all the pollutants. Moreover, some studies report damage costs, which are preferred by Miller, and some report control costs, including costs for CO_2 that are derived from carbon sequestration cost figures. Miller states that he takes these deficiencies into account when selecting the cost range for each pollutant. Miller reports that the $/gram figures he selects for his external cost calculations are well within the range of pollutant costs proposed by the Commission on Economic Instruments in Environmental Policy to the Swedish Parliament in 1990.[9]

From these selected damage values (in $/gram for each of the above-mentioned pollutants) and from the national average estimated emissions for automobiles and light trucks obtained from several sources, Miller estimates total light-duty vehicle air pollution costs at approximately $120 billion to $220 billion per year. These figures include air pollution damages to health, vegetation, and materials including global warming and acid

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[9]The Swedish government is currently implementing a policy of charging for many of the external costs that are associated with transportation activity, including air pollution.

rain costs. Miller cites several older studies for comparison and concludes that previous estimates neglected major costs such as global warming and acid rain costs, or they undervalued the risk to a human life. Miller also cites more recent studies that only consider one or two types of damage. For example, the American Lung Association estimates human health costs from auto pollution at between $4 billion and $93 billion per year. Also, for the Los Angeles air basin alone, the South Coast Air Quality Management District estimates human health and agricultural damage from autos at $3.65 billion to $7.3 billion per year. It might be possible that Miller's figures could be underestimated as not all effects and damages have been quantified or even studied, and as these costs are based on pollution damages from power plants, which tend to be based outside of high population areas.

Finally, one can compare Miller's estimates (see Table 2 below) with MacKenzie's original range of estimates ($10 billion to $200 billion). If MacKenzie's global warming estimate is included (see Table 1) and the total is multiplied by 50%, the range is then from $18.5 billion to $113.5 billion per year for air pollution externalities, compared with Miller's estimate of $120 billion to $220 billion.[10] While the two studies' low-end estimates vary by a factor of 6.5, the high-end estimates vary only by a factor of two, lending some credibility to the numbers, especially since different methods were often used to derive them.

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[10]To be technically correct the studies' dollar amounts should be discounted to provide an accurate comparison for the year of interest. However, because the studies cited here have been completed so close temporally and the discount rate is low (about 3%), the difference will be ignored in this work.

TABLE 2

MILLER -- ANNUAL EXTERNAL COSTS ($ BILLIONS)

Air Pollution, Global Warming, and Acid Rain	120 - 220
Water Pollution	1.3
"Energy Costs," Including Security Costs	41 - 146
Total	162.3 - 367.3

Global Warming Damages

MacKenzie states that given large scientific uncertainties, it is not possible to accurately estimate the actual costs of the risks of climate change. In this case, a substitute method such as mitigation cost or control cost would be used. MacKenzie cites a study that uses a substitute method for figuring the cost effects of climate change. This study estimates that a phased-in tax on all fossil fuels of $60 (1990 dollars) per ton of carbon would cut U.S. emissions to 80% of the 1990 level by 2005 and would stabilize carbon emissions indefinitely from then on. Such a tax would affect coal consumption more than any other fuel. From this carbon tax, MacKenzie comes up with an external cost estimate for climate change of $27 billion.

This figure can be regarded as arbitrary, though, as it reflects what it would cost motorists if such a tax on carbon were phased-in, and it has little if anything to do with the actual damages that climate change may bring about. Also, stabilizing carbon at 1990 levels by the year 2005 seems rather arbitrary, because this proposition most likely does not guarantee that climate effects are mitigated. This of course assumes that significant global warming effects will occur, which now seems to be the scientific consensus. What is noteworthy, however, is that the cost per ton of carbon adopted in MacKenzie's analysis is not very different from the figure derived by Pace University (reviewed later on in this work) from the cost of carbon sequestration through forestry. As actual damage costs due to global warming may very likely be impossible to predict, at least with today's knowledge, costs predicted by alternate methods may be the only option available.

Finally, if preventative measures are taken, the possibly huge costs of global warming could be avoided.

Water Pollution Damages

Although there has been little attention focused on the gasoline-fueled light-duty vehicle's contribution to water pollution so far, evidence exists that the contribution may be significant. Some of the pollutants contributing to water pollution include asbestos, lead, particulates, road salts and other de-icing chemicals, discarded engine coolant, petroleum residuals, oil and gasoline leaks, oil runoff on streets, and various detergents (Miller and Moffet 1993). (Note that some of these pollutants are associated with vehicle use, and not necessarily petroleum per se.) Some of the effects of water pollution include polluted water supplies, loss of fish and wildlife, stunted or destroyed vegetation, and some of the human and animal health and material damages similar to those caused by air pollution.

Miller estimates the total water pollution damages caused by automobiles to be about $3.8 billion per year. Some of these costs are attributed to the action of driving itself and not specifically to petroleum, such as the damages caused by salts and de-icing chemicals. These costs are estimated by Miller to be $1.25 billion/year. After deducting the de-icing costs, the total water pollution external cost is $2.55 billion/year. Of the $2.55 billion, Miller assumes $1.25 billion for the cost of all other contaminants, presumably lead and discarded engine coolant, among others. (He assumes that "the cost of all other contaminants is just equal to the salt and de-icing costs.") For the purpose of being conservative, this $1.25 billion will also not be included in Miller's aggregation in this work, as it is unclear how much of this cost is attributable to petroleum-fueled vehicles per se. The remainder is then $1.3 billion.

The studies that Miller uses to estimate damage from oil and petroleum probably underestimate costs, as they assess clean-up costs rather than actual damage costs. One study cited, conducted by the Office of Technology Assessment in 1991, estimates that cleaning up leaking underground gasoline storage tanks could cost as much as $32 billion over the next 10 to 20 years. Using the statistic that 40% of all petroleum sold in the U.S. is used by automobiles and light trucks, Miller comes up with a conservative estimate of $0.6 billion per year. Miller states that it is unclear how much of these costs will actually be passed on to consumers of petroleum in the future, which may reduce the estimate. However, he adds that clean-up efforts will not eliminate all damages. In fact, leaking petroleum tanks may damage underground water supplies, which may be very difficult if not impossible to clean up.

Another study Miller cites looks at the costs to clean up oil spilled onto surface waters. A 1979 Department of Transportation study estimated that $200 million (1990 dollars) would be needed to clean up an average of 10 million gallons of oil spills each year. Using more recent studies that show that the amount actually spilled on surface water alone is underestimated by at least 100%, Miller estimates $200 million attributable to cars and light trucks, as 40% of petroleum is burned by cars and light trucks. Again, this value is probably underestimated as the actual damages imposed on ground water, lakes, streams, and other amenities are likely to be greater than the cost of cleaning up. Indeed, clean-up efforts often fail to restore the environment to its pre-spill conditions, and they can do nothing about the losses suffered between the time of the spill and the cleanup, especially for large spills. Experience with restoration efforts also suggests that even if clean-up efforts are undertaken, it may take decades for the environment to be restored to its previous state, and even then the evidence seems to indicate that the restoration is partial.

It is unclear from Miller's analysis where the remaining $0.5 billion of his total $3.8 billion/year estimate comes from. Although Miller discusses other sources of water pollution such as the cleaning of oil tankers, runoff from streets, and the draining of crankcase oil into the ground, it is not explicitly stated how much of a cost he ascribes to these particular sources, although one can assume that is where the $0.5 billion comes from. For Miller's external cost aggregation, the $1.3 billion/year figure stemming from damages caused by oil and petroleum will be included in table 2.

MacKenzie's report does not address water pollution at all. It is evident that much further work needs to be done so that more reliable estimates for the contribution of the use of petroleum as an automotive fuel to water pollution can be obtained. Work especially needs to be done on the damages caused by accidental oil spills and routine cleaning of oil tankers, the runoff from streets, the draining of crankcase oil into water and soil, and the leaking of petroleum tanks into the soil and groundwater. Available studies do not seem to address these damages very reliably or completely.

Energy Security Costs

Energy security costs consist of the costs related to relying on imported oil. Currently, the U.S. imports nearly half of its total petroleum supply. By the year 2000, this figure is expected to increase to about 60% (Miller and Moffet 1993; Sperling and DeLuchi 1989). Imports are likely to continue increasing if alternatives to oil are not developed, given that the U.S.'s production and discovery rates have been declining rather steadily since the 1970's, even with increased exploration rates and newer technology for finding oil (Hall, Cleveland, and Kaufman 1992). This large import ratio has several disadvantages which include a large trade imbalance, the possibility of oil price volatility, and possible supply disruptions. Each has significant and real economic costs, regardless of how difficult they may be to quantify.

MacKenzie attempts to estimate a cost for dependence on imported oil. Recent analyses he cites suggest that increasing petroleum imports may not have such a significant effect on the international price of oil as once thought. MacKenzie thus regards the impact of increased U.S. demand for oil on world prices as negligible. The costs that arise from general U.S. dependence on oil (e.g. trade imbalance costs) and the economic costs that can occur from interruptions in supply, although real, are very difficult to assess and reliable estimates are not available. MacKenzie therefore uses an estimate of the costs of mitigation programs (such as U.S. protection of the Persian Gulf) as the next-best method to approximate these costs.

In August 1990 Iraq invaded Kuwait and the price of a barrel of oil jumped. Then-President George Bush responded by launching Operation "Desert Storm, " where 400,000 American combat troops along with planes, ships and other machinery of war were sent to Saudi Arabia. "We want to build an energy future that's based on a range of diverse sources so that never again will this nation's energy be swayed by events in any single country."--President George Bush, 1991. (Defending his energy policy proposals by acknowledging that oil motivated the war against Iraq) (Greer 1993).

Mitigation costs include the costs of the strategic petroleum reserve (SPR) and military presence in the Persian Gulf as strategies designed to protect the U.S. from abrupt supply disruptions. Note, however, that trade imbalance costs are not addressed in this substitute method. MacKenzie's estimate for the sum of these costs attributable to vehicles is $25.3 billion per year, half of the total amount of $50.5 billion since motor vehicles in general account for half of U.S. petroleum consumption. The total sum consists of $50 billion for maintaining a sizable military presence to protect the Middle East region during peacetime (taken from a study done for the Cato Institute), and $0.5 billion per year in appropriations for facilities and oil for the SPR. For comparison, Harold Hubbard (1991) of Resources for the Future stated that in 1989, between $15 billion and $54 billion was spent by the U.S. Department of Defense to safeguard oil supplies in the Persian Gulf. These numbers do not include the costs of actually engaging in war.

MacKenzie admits that this estimate may be too high, as perhaps there may be other reasons to maintain a military presence in the Middle East. And since consumers will, to some extent, pay for the petroleum when supplies from the SPR are used (depending on how much will actually be sold to the public and how much will be used by the government), the $0.5 billion per year for this expense may also be overestimated. It is unclear whether MacKenzie takes this consideration into account. MacKenzie does not estimate the macro-economic effects of being dependent on foreign sources of oil. MacKenzie's estimate of $25.3 billion/year is included in Table 1.

Miller cites studies which estimate government subsidies and military and macro-economic costs attributable to oil importation that range from $45 billion per year (assuming zero macroeconomic costs) to $150 billion per year. The range takes into account the fact that light-duty vehicles represent only 40% of total oil use. Included in this range are federal subsidies received by the oil industry each year. Because government subsidies are not addressed in this work, the $4 billion that Miller ascribes to light-duty vehicles will be subtracted from his estimate. However, government subsidies should not be ignored, as subsidies and their effects do affect the playing field for the fuels in this report. In Federal Energy Subsidies: Energy, Environmental and Fiscal Impacts, Douglas Koplow (1993) explains that even though some subsidies have been eliminated through the Tax Reform Act of 1986, energy subsidies in 1989 still favored mature, conventional energy sources by a factor of about 10 over non-conventional energy sources, and that infrastructure decisions and other investments have been based on past subsidies, the effects of which linger long after the subsidy itself has been phased out.

Miller's analysis thus gives $41 billion/year as the cost of military expenditures, the strategic petroleum reserve, the risk of supply disruptions, and losses in trade income. It is derived from studies cited by Miller which state that the sum of these costs may exceed $20 per barrel.

Finally, Miller assumes macroeconomic costs between $0 and $105 billion/year. This range seems rather wide. Examination of a study (Broadman 1986) cited by Miller confirms the wide range. Here, Broadman argues for an oil import premium based on the difference between the social and private marginal cost of imported oil. However, a later work by Broadman and Hogan (1988), also cited by Miller, states that Broadman's earlier range "encompasses all arguable values for input assumptions" to Broadman's model, and that they attempt to narrow the range "by choosing more plausible parameter values and recognizing their interactions." (Broadman's model consists of an economic component-- in that changes in oil prices will influence U.S. macroeconomic performance and a security component that reflects the "market imperfections associated with the total costs of oil supply disruptions and with the risks arising from vulnerability to such disruptions.") Broadman and Hogan present arguments and a sensitivity analysis and conclude that an optimal tariff for imported oil would be $10/barrel, narrowing down Hogan's earlier range of $0 to $124/barrel. This $10/barrel translates to a cost of about $8.5 billion/year for light-duty vehicles' share. Miller's original numbers excluding subsidies, however, are included in his cost aggregation in Table 2. It is apparent, though, that macro-economic costs are fertile ground for further analysis.

Total External Cost Estimates

From Tables 1 and 2 shown previously, total external costs are $62.3 billion per year in MacKenzie's cost aggregation, which translates to $0.46/gallon of gasoline. In Miller's analysis, total external costs range from $162.3 billion to $367.3 billion per year, which translates to $1.59 to $3.60 per gallon of gasoline. MacKenzie's total external cost estimate was divided by the annual amount of oil used by private highway vehicles in 1989. The number MacKenzie attributes to private highway vehicles is 8.9 million barrels per day. This includes 1.4 million barrels a day of other fuels which consist of diesel fuel, liquefied gases, and kerosene when they are used to operate vehicles on highways (Energy Information Administration 1991). Miller's external cost estimate is divided by the portion attributable to light-duty vehicles, which Miller claims is 40% of the 16 million barrels per day used in the transportation sector. It is important to reiterate that these numbers can be viewed only as preliminary "starting point" estimates, and also that one cannot compare the totals very strictly, as some externalities were not estimated, and the authors sometimes estimated different damages. It is also obvious that additional work needs to be done so that more comprehensive and credible external cost estimates can be made available for petroleum-fueled vehicles.

The external costs of battery-powered electric vehicles will now be estimated. This will be accomplished by reviewing two studies which estimate the environmental costs of electric power, and by reviewing the literature for estimating the external costs of batteries.

CHAPTER VI

External Costs of Battery-Powered Electric Vehicles

The environmental impacts of battery-powered electric vehicles include the impacts from the generation of electricity for the recharging of batteries and the impacts from the manufacturing, recycling, and disposal of the batteries. If mining of battery materials is required, the impacts of mining also need to be addressed, and external costs estimated. In this work, it is assumed that lead-acid batteries will be the first used for electric vehicles. However, other batteries may become commercially available as well for electric vehicles and may have external costs higher or lower than lead-acid batteries.

Currently, between about 10 and 25% of conventional lead-acid batteries are not recycled but are dumped in landfills (Fischetti 1991; Makower 1992; Nadis and MacKenzie 1993; IEA 1993). Each of these batteries contain about 18 pounds of lead and one gallon of sulfuric acid, both of which can seep into the ground and into groundwater. Because the environmental impacts of the dumping of lead-acid batteries could be quite significant, especially if lead-acid batteries will be used to power electric vehicles, recycling could be better encouraged by requiring deposits on the batteries. Also, the external costs of battery manufacturing, recycling, and the mining of materials need to be assessed.

The California Air Resources Board (1994) is currently in the process of quantifying emissions from manufacturing and recycling of lead-acid batteries. Preliminary estimates of emissions of battery recycling are included in their report. The pollutants emitted in recycling are estimated to be, per battery: 0.004 pounds of NO_x, 0.001 lb of ROG, 0.0058 lb of CO, 0.02 lb of particulates, and 0.0008 lb of SO_2. CARB states that these emissions estimates are likely to be conservative, as an expansion of recycling facilities to serve the electric vehicle market will likely use newer, lower-emitting technologies. Using pollutant cost figures (in $ per gram) compiled by Miller and Moffet (1993) from their review of previous studies, the external cost for emissions from battery recycling is estimated to be about $0.04 per battery, which is insignificant compared to the market cost of a battery. It seems reasonable to use Miller and Moffet's data (which were estimated for pollutants emitted by power plants) because battery manufacturing and recycling facilities are likely, like power plants, to be located in more remote areas. If the external cost for manufacturing emissions were also assumed to be about the same, the total external cost for batteries may indeed be quite low. However, this assumes that batteries are actually recycled. In order to encourage recycling, instruments such as deposits must be in place. Such policy instruments will avoid the possibly much higher external costs when batteries are dumped in landfills, and will substantially reduce the external costs associated with the mining of new materials.

The external costs due to the impacts of the generation of electricity have been estimated in several studies, two of which are reviewed here. These two reports are considered the most comprehensive available at this time. The first study was conducted by the Pace University Center for Environmental Legal Studies for the case of the U.S. This study was published in 1991. The second study was done by Olav Hohmeyer for the case of the former West Germany, and was published in 1988. They are discussed separately here because it will help the reader follow the studies, which are quite detailed, when they are treated independently. Also, the studies take somewhat different approaches, and the differences in currency and other economic and geographic situations do not lend themselves to comparisons. However, these studies were chosen for review because of the depth of their analysis and because they are regarded by analysts as being the most credible and complete at this time. Pace University acknowledges that besides their report, Olav Hohmeyer has done the only other recent comprehensive study of environmental externality costs of electricity generation, hence another reason for that study's inclusion in this work. Pace University further states that the only previous comprehensive study in the U.S. of the environmental externality costs of electricity generation was done by Michael Shuman and Ralph Cavanagh in 1982, and their report draws heavily on Shuman and Cavanagh's original work.

Clifford (1984) has also presented a rather comprehensive Ph.D. thesis on the external costs of electric power from coal-fired and nuclear power plants, which is not reviewed here. Clifford's focus is on the state of California, rather than the nation. More importantly, though, his study is considered to be too outdated for the purpose of this analysis, which is to review the most recent and relevant works available at this time. This is especially important in a field like environmental costing, where the more that is learned about pollution and other externalities the more costly or harmful they appear to be (OECD 1993). Indeed, Clifford's external cost estimates are a small fraction of the other more recent studies' estimates, one reason for which is his reliance on older data and studies. Another reason is simply a lack of engineering experience on the past performance of technologies from which meaningful data could be derived. For the nuclear fuel cycle, for example, Clifford uses the 1980 BEIR III review, where the dose-response relationship for cancer fatalities is approximately one-fifth that of the 1989 BEIR review. Therefore, Clifford's thesis will not be reviewed here. Pace University's report will now be discussed.

Pace University Study--Fossil Fuel Plants

Pace University Center for Environmental Legal Studies, in their Environmental Costs of Electricity report, reviews studies that quantify the external costs of various environmental impacts resulting from the generation of electricity and aggregates these costs to get "starting point" environmental cost values for various generating technologies. The report is primarily intended to aid the estimation of the external costs of the generation of electricity, as the authors admit that their evaluation is far from being complete. The costs that result from this study are therefore meant to be a "starting point" for the environmental impacts of electricity, as fuel extraction, processing and transportation costs were excluded in their evaluation because of limited resources. Only the impacts from the operation of the utilities through the disposal of the waste at the end of the fuel cycle were included in Pace University's analysis. Non-environmental externalities such as national security costs and public subsidies were also excluded from the study. Nevertheless, it is probably the most thorough report available on the environmental costs of electricity at the time of this writing, being the result of a major contractual effort by economists, energy and utility experts, attorneys, environmental professors, many law students, and government agencies. Moreover, since analysts and economists have focused the most effort on estimating the environmental costs of electricity (as compared to the other forms of energy evaluated in this work), it is also the most detailed and lengthiest report reviewed. Alan Krupnick (1993), senior fellow at Resources for the Future, describes it as being a "widely cited study, ...commendable as the first attempt at collating and analyzing the vast scientific and economic literature" for estimating social costs. For these reasons, this work depends heavily on Pace University's report.

Pace University's objective is to obtain environmental cost figures expressed in dollars per kilowatt-hour ($/kWh) for each fuel used in the generation of electricity. The researchers attempt to use actual damage cost figures whenever possible, rather than control cost figures. Included in the report are coal, natural gas, oil, nuclear power and renewable electricity technologies. Their approach is to estimate the average number of pounds of each pollutant emitted per kWh for each technology. The pollutants studied are SO_2, NO_x and ozone, CO_2, particulates, acid deposition, and land and water pollution impacts. Costs to society for each pollutant or impact in dollars per pound ($/lb) are obtained from a review of the literature on the damages and respective costs of various environmental impacts. From these two sets of data, environmental costs in $/kWh for each generating technology can be obtained. This approach is intelligent as the $/lb pollutant figures can possibly be used to estimate environmental costs for new technologies and for other production processes that emit pollutants. Pace University's review of the literature on the estimation of $/lb figures for the above-mentioned pollutants will now be discussed. Note: Quite a few people contributed sections and research to the Pace University report, and the sections were written by several authors, explaining the sometimes different treatment given to the various sections.

CO2 and Other Greenhouse Gases

Pace University analysts attempt to determine the cost of the climatic environmental impacts resulting from the production of electricity using fossil fuels. There is consensus in the scientific community that increases in greenhouse gas emissions, of which the production of electricity is a significant contributor, will result in climate change. The nature and extent of the change, though, as well as the consequences for humanity and ecosystems are uncertain.

Of the greenhouse gases, CO_2 has accounted for two-thirds of the warming to date, and it is predicted to account for about 80% of future climate change given the current trends, according to Pace University. In addition, in the U.S., electric utilities are accountable for about one-third of all of the carbon emitted from fossil fuels, and if the entire fuel cycle were included, electricity's proportion would be significantly larger. Because the generation of electricity contributes significantly to climate change, the internalizing of the environmental costs due to the effects of global warming is a critical step in the promotion of economic efficiency and other benefits to society.

Pace University explains that calculating the costs of the effects of global warming is extremely difficult if not impossible, given that the effects are both speculative and likely to be enormous. Not only are the effects of global warming (e.g. climate change, change in rain patterns, etc.) difficult to predict accurately, the impacts of those effects are speculative and unmeasurable in dollars. Some of these impacts include loss of land due to the inundation of coastal areas, loss of biodiversity, and extremes in weather and storm conditions. A valuation of the climate change impacts is rather impossible, at least at this time. Therefore, the approach Pace University finds most appropriate for this purpose is to calculate the cost of sequestering the CO_2 by planting trees or other vegetation.[11] The trees will remove CO_2 from the atmosphere and store it in plant material. If the cost of burning fuel includes the cost of capturing the CO_2 released by the burning of fossil fuel, then energy choices would reflect the total costs. Pace University notes that tree cultivation is an approach that lends itself to concrete cost analysis far more than measuring environmental damages from global warming or other methods of mitigating the effects. The tree-planting strategy also provides two separate benefits--1) mitigating the effects of global warming and 2), helping reduce energy consumption and increasing the use of more environmentally friendly technologies due to the internalizing of external costs.

Pace University reviews cost calculations of various projects that were proposed to sequester CO_2 emissions. One project is an offer by Applied Energy Systems, working with the World Resources Institute (WRI) and CARE, to sequester 16.3 million tons of carbon over 40 years by planting trees in woodlots and promoting agroforestry in Guatemala. The total cost of the project, calculated by WRI, would be $14.3 million. If the project is successful, this would come out to be about $4.21 per ton of carbon sequestered, or $1.15 per ton of CO_2.

Pace University reviews the proposal and finds several reasons to believe that the costs of the project are significantly understated. For example, direct labor costs in the

[11] According to Buchanan, although it would probably not be feasible to actually plant enough trees to make up for current and future world-wide carbon release rates, the cost of tree planting is a "reasonable first approximation" for the cost of the effects of global warming.

tree planting were not included, as WRI assumed that the farmers' labor could be compensated with food aid. The carbon sequestration calculations did not address potential losses from pests, natural disasters, social or political unrest, or other institutional barriers and risks. There were no provisions for forest rangers, fire fighters, or for any significant measures to help minimize the risk of failure. The cost of project development and follow-up evaluation were not included in the figures. Pace University relates further that the amount of carbon to be saved was ultimately a guess, as the land on which the trees were to be planted could be too depleted to support the carbon fixation rates that were assumed by WRI. Pace University concludes that a high-risk project such as this should allow for the increased cost, decreased effectiveness, social, political, and scientific shortcomings, and also should consider historic emissions, so that more reliable estimates for "global warming" costs could be established.

Pace University reviews another similar project, based in Costa Rica, which was designed to sequester carbon by stopping rapid deforestation through forest management and reforestation. The Conservation Foundation and World Wildlife Fund (CF/WWF) estimated the carbon sequestration costs at about $2.64 per ton of carbon. Again, Pace University believes the costs are surprisingly low. CF/WWF assumed that the undertaking would be completely successful, even though, at the time of Pace University's analysis, the existing forests in Costa Rica were being rapidly depleted and were likely to be almost completely deforested without the program. As in the WRI/CARE proposal, protection measures and margins for risk of failure were likewise not included. Therefore, Pace University finds this proposal also inappropriate for the determination of carbon sequestration costs.

Several "macro cost" estimates have been made for using forest plantations to offset all carbon emissions, and these are also reviewed in Pace University's report. Chernick and Caverhill review these generic estimates and adopt a figure of $80 per ton of carbon, also adopted by the Tellus Institute. Schilberg estimates $54 per ton, also adopted by the California Energy Commission. Koomey compares several estimates and proposes $84 per ton. Pace University's opinion is that these general and broad estimates, because they are not tailored to specific locations or the region's social and economic needs, do little more than establish the scale of the problem.

Buchanan, according to Pace University, estimated the cost of sequestering carbon in the Pacific Northwest to be $17.08 per ton, using a 3% discount rate and no taxes. The costs are based on land which is currently planted with trees as it is clearcut. Pace University believes that the costs for marginal sites would be higher, as additional land would likely be higher-priced, less accessible, or less productive. Using Buchanan's assumptions and a 6% discount rate, Pace University brings the cost to $26.23 per ton of carbon. A 12% discount rate would give a cost of $47.45 per ton of carbon, which is similar to Schilberg's $54 per ton. Pace University also reports Dudek and LaBlanc's estimate of the cost to use the Conservation Reserve Program to subsidize the planting of trees on farms as $53 per ton of carbon at a 3% discount rate. The trees will reduce erosion and surplus agricultural production, and at the same time sequester carbon, although at a rate that is considered optimistically high by Pace University.

In assessing these proposals and studies, the reviewers conclude that the most reliable estimates are those from temperate industrial countries, which have established commercial forestry and more stable political climates. They state that more and better data is needed from tropical countries to be able to use estimates from those countries. Pace University believes the Buchanan, Schilberg, and Dudek estimates are optimistic, since they use the cost of trees already planted, not the cost of additional planting which "might reasonably represent the marginal greenhouse-mitigation option." A Chernick and Caverhill study focusing on the marginal cost of sequestration gives $80-$120 per ton of carbon, although at utility financing rates. Pace University finally adopts the value of $50 per ton of carbon, which is $13.60 for a ton of CO_2, or $0.0068 per pound of CO_2. This value falls in the middle of the range of carbon sequestration costs estimated for temperate, industrialized countries. Pace University's selected $/lb figures for fossil fuels are shown in Table 3.

TABLE 3

PACE UNIVERSITY -- POLLUTANT COSTS ($/LB.)

CO_2			0.0068
SO_2	Human Health	1.77	
	Materials	0.12	
	Visibility	0.14	
		Total	2.03
NO_x	Human Health	0.63	
	Vegetation	0.01	
	Materials	0.01	
	Visibility	0.17	
		Total	0.82
Particulates	Human Health	0.36	
	Visibility	0.83	
		Total	1.19

Effects of Sulfur Dioxide (Excluding Acid Rain Effects)

Sulfur dioxide and its reactants cause human respiratory health problems, degrade visibility, cause vegetation and materials damage, and affect plant and animal habitats. Electric utilities, through their use of sulfur-containing coal and oil, are responsible for two-thirds of the sulfur dioxide emitted in the U.S., according to the report. Pace University reviews several studies of the damage caused by sulfur dioxide and its derivatives to human health, materials, crops, and visibility.

For the human health effects of SO_2, Pace University reviews an analysis by ECO Northwest of three of their earlier studies of power plant emissions and the pollutants' impacts on humans and their environment. Using these studies and $4 million (in 1989 dollars) as the value of the risk to a human life and $400,000 as the value for morbidity, (instead of ECO's figure of $3 million for mortality), Pace University estimates that the mortality damage due to SO_2 and sulfates is on the order of $1.72 per pound of SO_2 (in 1989 dollars). The value for morbidity is $0.05/lb. Because the northeast region of the U.S. has a population density two to ten times greater than the areas studied by ECO, the same emissions would affect that many more people, for roughly two to ten times the cost. Pace University assumes a linear relationship between the number of people affected and the population density, which is reasonable. The range for health effects is then from $1.72/lb to $17.20/lb, depending on the population density.

An earlier (1979) study by Mendelsohn estimates the damages from a power plant in New Haven to be $1.34/lb of SO_2 for mortality and $3.16/lb for morbidity, when adjusted to 1989 values and when using the $4 million figure for the value of the risk to a human life. Although New Haven is an area of high population density, a large fraction of the emissions from the plant blow out to the sea, explaining the low estimates. Pace University comments that Mendelsohn reports health benefits from NO_x emissions and no health impacts from particulates, which cause the analysts to question the SO_2 estimates. What is also interesting is the large disparity between the mortality and morbidity effects resulting from the ECO Northwest and Mendelsohn studies. ECO's study gives a morbidity estimate much smaller than the mortality estimate and Mendelsohn's morbidity estimate is larger than his mortality estimate. Pace University does not comment on this significant variation. What is obvious though, is that additional research and agreement on methods for acquiring more reliable estimates is justified. Pace University adopts the $1.72/lb for mortality and $0.05/lb for morbidity as conservative estimates for human health effects from sulfur oxide emissions.

For the crop effects of SO_2, Pace University reviews several studies, most of which do not distinguish between acid rain effects and direct sulfite and sulfate effects. A review by Krawiec (which differentiates between SO_2 and acid rain effects) reports estimates of the total national economic loss to agricultural plants at $85.5 million and to ornamental plants at $46 million (in 1964 dollars). Of the totals, damages due to SO_2

emissions were calculated to be $3.3 million and $3.0 million, respectively. Since national SO_2 emissions were approximately 25 million tons in 1964, the figure comes out to be about $0.13 per ton of SO_2 (in 1964 dollars) for agricultural crop damage, and roughly the same for ornamental crop damage. When calculated for 1989 using a 3% discount rate, the figure is $0.00027/lb of SO_2. Although the studies appear to underestimate total crop damage figures because certain costs are not included (e.g. the costs due to erosion or crop substitution), the costs due to direct sulfite and sulfate effects seem to be insignificant. When acid rain effects are excluded, Pace University concludes that there are no current estimates of the marginal cost of SO_2 crop damage, other than zero.

For an estimate of materials damages due to SO_2, Pace University cites a Krawiec review of several studies of the effects of SO_2 concentrations on the corrosion of materials such as galvanized steel, zinc, and other metals. These studies attribute 80 to 90% of the corrosion costs directly to SO_2. Three studies reviewed give SO_2 corrosion damage estimates of $0.34/lb., $0.12/lb, and $0.22/lb (all figures were converted to 1989 dollars). A study by ECO Northwest implies damage costs to be $0.017/lb.

Pace University states that none of these studies were reviewed to assess the validity of the assumptions made or the transferability of the results to other areas in the country. Therefore, only a rough idea of the order of magnitude of the damages can be determined. These damages are estimated to range from $0.017 to $0.34/lb of SO_2. Pace University adopts the middle-range $0.12 /lb figure for their report. Again, Pace University claims that these damages may be underestimated for highly populated regions, and estimates made ten to twenty years ago probably do not characterize today's situation accurately.

For the visibility effects of SO_2, Pace University reviews an ECO Northwest study which models the lost visibility due to a specific generation facility in Washington state. ECO's study models the visibility loss due to each pollutant and estimates visibility effects for various distances from the plant. Using an average value of $10 per lost km-year per person (derived from contingent valuation and hedonic pricing methods), ECO estimates losses in value due to SO_2 to be $0.11/lb (1982 dollars). Pace University updates this estimate to $0.14/lb for 1989.

The Mendelsohn study provides data which Pace University uses to come up with an estimate of $0.02/lb of SO_2. However, this figure is viewed with caution by the reviewers, as Mendelsohn provides no basis for his visibility impact estimate. Pace University therefore adopts the $0.14/lb estimate for their report. Since the population density of Washington state is low compared to other regions of the country, this estimate is probably conservative.

Pace University aggregates the estimates of damages caused by SO_2 which affect the various populations and the result is a total damage estimate of $2.03/lb for the 1989 year. The total estimate is comprised of generally conservative figures of $1.72/lb for mortality and $0.05/lb for morbidity, $0.12/lb for materials corrosion, $0 for vegetation damage, and $0.14 for visibility effects. Pace University cautiously states that the $2.03/lb figure should be used as a rough starting point of the environmental impacts due to SO_2 emissions. Further work must be done to address the effects not estimated, such as the effects on wildlife and ecosystems, and on culturally or historically significant structures. Older reports should also be updated to take the higher population density into account, because population enters directly into the calculations of many of the damage estimates.

Effects of NO_x and Ozone

NO_x is formed during the combustion of fuel when nitrogen in the air combines with oxygen, and it consists of chemical compounds such as NO and NO_2. Electric utilities are responsible for about one-third of all NO_x emissions, according to the report. Ozone is one of the products formed when nitrogen oxides and hydrocarbons from vehicle exhaust interact with oxygen in the presence of sunlight. It is recognized as the primary element of urban smog (often called photochemical smog) and haze.

Although there is strong evidence that exposure to ambient ozone can cause human health effects such as structural lung damage which may lead to chronic lung disease, lung cancer, and increased susceptibility to respiratory damages, the studies reviewed by Pace University give a wide range as to the extent of this damage. ECO Northwest performed a study in the state of Washington which resulted in an estimate for ozone-related mortality damages of $0.34/lb of NO_x emissions (1989 dollars). For the northeast, Pace University asserts that these damages could be between two and ten times higher.

There is a wide range of damage estimates for morbidity effects, with studies estimating costs of zero through $1.73/lb. Pace University finds it implausible that some studies report ozone-related deaths without ozone-related illness, especially since exposure to NO_X and ozone generally does not cause sudden death in healthy individuals. Rather, the pollutants aggravate existing respiratory problems and contribute to future lung problems, as there is some evidence that most inhaled ozone is never exhaled. Pace University reviews two studies that estimate the benefit of meeting the federal ambient ozone standard in the South Coast Air Basin region in California and chooses the more conservative estimate of $0.29/lb of ozone precursor for its cost aggregation. Pace University concludes that in the last twenty years, the state of knowledge on the health effects of ozone has grown considerably and that it may prove necessary to disregard the older studies. Total morbidity and mortality costs adopted by Pace University are $0.63/lb of NO_X emissions.

Pace University reviews an ECO study that give damages to grain, fruit, vegetable, and seed crops to correspond to a value of about $0.01/lb (1989 dollars) of NO_X emissions. Other ECO studies give lower estimates, and there is considerable disparity in them. Pace University adopts the $0.01 estimate in its cost aggregation, perhaps again because crop losses are highest in the highest population density areas, especially for the case of fruit and vegetable crops.

Pace University reviews an ECO report that estimates material damages due to NO_X to be on the order of $19/ton, or about $0.01/lb. A National Academy of Sciences publication reviews studies and estimates damage costs at $0.075/lb of ozone precursor, approximately half of which goes to damage to paint, with the other half going to damage to rubber materials. Pace University adopts the more conservative $0.01/lb (1989 dollars) for its cost aggregation.

Based on data from the ECO visibility study mentioned earlier, Pace University estimates the cost of the loss of visibility due to NO_X emissions to be about $0.17/lb in 1989 dollars. The site of this particular study seemed to have low ambient concentrations of VOCs, forming negligible ozone. In areas of the country with higher population densities (where significant VOCs concentrations from automobiles enter into the picture) this assumption will not be valid.

Pace University totals the above estimates for NO_x and ozone effects for a figure of $0.82/lb of NO_x emissions. The estimate is a rough starting point for NO_x-related damages because certain effects were not valued (e.g. the effects on animals and ecosystems). In addition, higher population densities need to be taken into account, and the dose-response relationships for health effects also add uncertainties. The $0.82/lb figure (broken down in Table 3) includes what appear to be estimates picked from the "best available" studies, most of which fit into the middle of available cost ranges, according to the report.

Acid Deposition

Pace University attempts to come up with a dollar figure per unit of emissions for the external effects of acid deposition (for both SO_2 and NO_x emissions) but is unsuccessful. In their search through the literature, no study or set of studies was found that would complete the necessary linkages in a consistent manner. Even the most recent compendium on the subject at the time of their study was neither fully comprehensive nor uncontroversial, according to the reviewers.

Pace University explains that one of the difficulties involved in the environmental costing of acid deposition is that emissions from particular sources, not the total emissions, for a specific receptor area must be determined. Because acid precursors (SO_2 and NO_x emissions) are carried in the atmosphere for one to ten days before they are deposited, it is very difficult to make the link from emissions to acid deposition, especially when approaching the problem from the marginal perspective of economics.

The second difficulty lies in the inability of scientists to quantify the marginal damages from each incremental unit of pollution. The damage function is not necessarily linear as pollution increases. Damages are site-specific, and depend very much on the environmental and stress factors already present. For example, lakes may have different thresholds at which point their buffering capacity is diminished.

Valuation of the damages is also not trivial. Although some studies attempt to put an economic value on the damages caused by acid deposition, the damages are not linked to the quantity of emissions released upstream, which is necessary for environmental costing. Further, Pace University researchers found that most studies lack sufficient quality and detail to produce damage estimates. Those studies that came up with damage estimates, though, found that the costs are not trivial. For example, one study valuing recreational fishing in the Adirondacks gave damage estimates of about $15 million for that area, and another estimated damages in the Adirondacks to range from $28 to $100 million per year. As the estimates typically considered the value of lakes for recreational fishing, they may be considerably understated. And putting a number on the ecosystem value of a region is a domain not yet entered in environmental costing studies. Also, Pace University analysts found no credible economic estimates that value acid deposition damages to U.S. forests. And although it is well known that acid deposition corrodes stone and other materials, credible studies in this area are lacking, especially when attempts are made to value cultural monuments and historic stone structures. One well-known European historic structure being corroded by acid deposition is the Greek Acropolis, for example.

Pace University asserts further that attempting to derive damage estimates that consist of components and values that can be rigorously defended will by necessity be an underestimate of the costs and may even trivialize the true effects of acid deposition. Pace University completes their discussion by stating that studies now underway will permit the necessary links to be established so that estimates may be possible in the near future, at least for freshwater fishing and materials damage.

Particulates

The major components of particulates from a power plant include ash (which is made up of heavy metals, radioactive isotopes, and hydrocarbons), sulfates, and nitrates. Power plants using fossil fuels to generate electricity are a significant contributor of particulate matter, according to the report.

Particulates cause human health effects by entering the lungs and reducing respiratory function in healthy humans or aggravating existing lung conditions. Pace University reviews a study conducted by Hall that estimates the benefits, in terms of avoided mortality and morbidity, for the South Coast Air Basin if the federal standard for PM10 (particulate matter under 10 microns) was met. Although Hall uses the "best" estimate of PM10 mortality available from a previous study, the uncertainties in the dose-response relationship are reported to be high. Pace University, using the "best" estimate and a value of $4 million for the risk to a human life, comes up with a figure of $4.25 billion in 1989 dollars. Using South Coast Air Quality Management District (SCAQMD) data, the PM10 reductions needed to meet the federal standard by 2010 are estimated to range from 37,595 to 476,325 tons/year. Hall's study thus implies that the average benefit for meeting the standard lies in the range of $4.50-$57/lb of PM10 in 1989 dollars. Pace University adds further that the marginal benefit of reducing PM10 levels is likely to be higher than the average benefit estimated.

Using a similar approach for morbidity effects (Hall estimates a reduction in restricted activity days due to meeting the federal standard) and a value of $66 for each restricted activity day, Pace University estimates a value of $1.01-$12.90/lb of PM10.

Another reviewed study was performed by ECO Northwest. Here ECO estimated 0.2 deaths per year for a plant located in the most populated area of Washington state. Using the same method as above, Pace University estimates the value for PM10-related mortality to be $0.33/lb (1989 dollars). The same study estimates that the PM10 emissions will cause 31 cases of bronchitis. The value that Pace University estimates for PM10-related morbidity here is $0.03/lb. A second ECO study also confirms these numbers. Pace University therefore adopts $0.33/lb for mortality and $0.03/lb for morbidity as conservative estimates for their report's external cost aggregation.

Using the ECO study that estimates impairment factors for each pollutant contributing to degraded visibility and the value of $10/person-km per year obtained from contingent valuation and hedonic pricing studies, a cost of $0.83/lb of particulates is derived for the visibility effects of particulates. This cost per pound figure is adopted by Pace University and included with the other pollutants' figures in Table 3.

In the three ECO studies reviewed by Pace University, damages to vegetation due to the emissions of particulates were estimated to be zero. Pace University researchers were unsuccessful in finding other studies with useful estimates for crop damages.

ECO studies reviewed show that to at least 2 decimal places, materials damage due to particulate matter is found to be zero.

For the effects of particulates on wildlife, endangered species, and ecosystems, an ECO study reviewed by Pace University states that animals have the same sensitivity to air particulates as do humans, and wild plants and ecosystems may be affected as well. However, ECO gives particulate-related damages to animals and ecosystems a value of zero, perhaps because the valuing of wildlife and ecosystems is a relatively new and/or especially difficult domain in environmental costing. Also, the current general practice in environmental costing is that environmental effects lacking damage estimates are automatically set to zero.

For the summation of the total damages due to particulate matter, Pace University uses the more conservative health effects cost of $0.33/lb for mortality and $0.03/lb for morbidity, along with the $0.83 estimate for visibility losses, for a total of $1.19/lb for particulates. Costs due to vegetation, materials, and ecosystem effects were assumed to be zero. The cost of health effects adopted here seems to be low compared with the visibility estimate. Pace University concludes by stating that the uncertainties in the reviewed studies are high, and that effects such as damages to wildlife and ecosystems are not well understood and are potentially undervalued. (It would be hard to imagine that they aren't greatly undervalued!) The value of $1.19/lb of particulates is considered a very rough starting point, as damages could be higher for highly populated areas and for areas where visibility is very important. Finally, once the effects of particulates on animals and ecosystems are better understood, these damages could also be accounted for.

Land and Water Pollution Impacts

Pace University reports that power plants generate solid and liquid wastes and cooling system discharges in their normal operation and maintenance procedures. The wastes must be disposed of in landfills and they may have surface water, groundwater and land use effects. Significant amounts of land are required for plant sites, fuel storage, and transmission lines. Large quantities of water are also required for cooling procedures and maintenance, the removal and return of which impacts fish populations and other organisms.

Some of the effects which are described in Pace University's report are: water consumption impacts, impingement and entrainment of fish and other sea life due to the intake of cooling water, impacts of cooling water discharge, especially when thermal discharges contact wetland areas, waste water contaminant discharges, releases of radioactive water pollutants, land use impacts for generation, transmission, and waste disposal, including associated ground and surface water impacts, and effects of power transmission on organisms, including the effects of electromagnetic fields.

Studies reviewed show that these impacts could be substantial. For example, a study valuing impingement effects using mitigation costs and species-specific values for fish estimated annual costs of about $1.42 million for the effects of the use of cooling water for a 500 MW nuclear plant. Costs due to fish entrainment may be even higher. Although Pace University analysts do not generally subscribe to the use of mitigation costs to establish externality values, they report external costs obtained from mitigation costs for impingement effects that range from $0.00006 to $0.00164 per kilowatt-hour for nuclear plants and $0.00002 to $0.00059/kWh for fossil-fuel plants. These costs do not include entrainment impacts and other water pollution effects. The mitigation actions from which these costs are derived include hatchery programs, modifications to cooling systems, and closed-cycle cooling, which is viewed by the industry as an upper-bound figure for these effects. It is likely that the cost of a modest hatchery program may be a small portion of the value that is lost due to the impingement of many species. Moreover, because hatchery programs often only restock one or a few fish species, the ecosystem may even be further disturbed. Further research is also warranted, for the reason that costs and impacts are very site-specific. Pace University asserts that until more credible estimates are available, the best estimate to apply is the cost associated with closed-cycle cooling, known to be the most effective mitigation strategy.

Pace University was unable to find studies that place monetary values on many of the other land and water impacts. And because of the site-specific nature of many of these effects, it is difficult to make generalizations, even when impact studies are available. For example, while land use requirements for fossil fuel plants are generally well-known (a Tellus Institute study estimates land use requirements of 1.24 acres per MW for most coal-fired plants and 1.00 acre per MW for oil and gas-fired plants), the external costs due to the plant sites, fuel piles, waste dumps, and power lines can be very site specific. Factors that may influence these external costs include the proximity of the plant to scenic and recreational areas and wildlife and endangered species, and the potential for groundwater contamination. Mitigation measures already in place also depend on state and local regulations. For other effects such as the effects of exposure to electromagnetic fields from power lines, the present state of knowledge is inadequate for making credible judgments.

The analysts conclude that the valuation of land and water impacts is not as advanced compared with other categories of externalities, and that additional research is needed in this area, especially in the assessment of coal combustion and maintenance wastes and in fish impingement and entrainment. Nonetheless, the New York Public Service Commission has adopted values for fossil fuel plants' land use and water pollution externalities for use in new capacity bidding programs. An amount of $0.01/kWh is assigned to water-related externalities and $0.04/kWh is assigned to land-use related externalities. These figures were derived from studies conducted by the Bonneville Power Administration and were based on the cost of controlling or mitigating residual water and land use impacts. In their aggregation, however, Pace University does not include land and water use impact costs, which makes their final cost estimate even more conservative.

Aggregated External Costs for Fossil Fuel Plants

Pace University, using the pollutant cost figures (in $/lb, shown in Table 3) ascribed earlier to CO_2, SO_2, NO_x, and particulates, and using estimates of pounds of emission per million BTU (mmBTU) of energy input for each of the technologies, derives external cost figures for the various generation technologies. For the purpose of simplification, it will be assumed that most of the power for recharging EVs around the year 2000 or so will be derived from existing technologies. Pace University also gives estimates for several new technologies, such as Atmospheric Fluidized Bed Combustion coal-fired plants, but the proportion of power derived from these newer technologies is assumed to be relatively low. The following external cost estimates are for existing technologies.

For existing boiler coal-fired power plants, burning 1.2% sulfur coal, Pace University arrives at an external cost of $0.068/kWh delivered. This is the external cost for plants without scrubbers. For existing boiler coal-fired power plants equipped with scrubbers, the external cost is $0.045/kWh delivered, according to Pace University.

According to the Energy Information Administration (1994), the percentage by plant capacity of coal-fired steam-electric generators in the U.S. that are equipped with scrubbers is about 22%. Assuming that plant capacity factors are equal, an average external cost of $0.063/kWh delivered is derived for coal-fired power plants

For natural gas-fired power plants (existing steam plants), Pace University arrives at an external cost of $0.012/kWh delivered.

For existing boiler oil-fired power plants, burning 1% sulfur oil, Pace University arrives at an external cost of $0.045/kWh delivered.

The external cost figure for nuclear power plants has also been estimated by Pace University. A discussion of this endeavor is presented next. After this figure for nuclear power has been established, an estimate of the external cost ($/kWh) for the projected national average marginal mix of power used to recharge electric vehicles will be calculated.

Pace University Study--Nuclear Power Plants

Several studies are reviewed which estimate environmental damages caused by nuclear power plants. Pace University acknowledges that the damages from nuclear power plants are more difficult to assess than those from fossil-fuel plants. This is so for a variety of reasons: 1) determining the frequency and magnitude of non-routine releases of radiation is difficult; 2) assigning the probabilities and consequences of major nuclear accidents is even more problematic; 3) there is uncertainty with regards to the health effects of low level radiation; and 4) costs associated with the storage and disposal of high- and low-level waste, including decommissioning, are uncertain.

External Costs of Routine Operation

Pace University reviews three studies which estimate the number of sudden occupational deaths (falls and other accidents) per Gigawatt-year at large nuclear facilities. The estimates range from 0.01-0.15 deaths/GW-yr. Pace University asserts that because these studies relied on data that was at least 10 years old, they are likely to underestimate future occupational injuries because of the aging of nuclear power plants. A good example is the 1986 event at the Surry power station, where a corroded pipe ruptured, releasing steam and scalding eight workers, four of whom died from their injuries. Similar problems at other facilities have arisen in the late 1980s, because of aging and maintenance deficiencies. Because of aging problems and capacity factor assumptions in the studies, Pace University adopts the high estimate of 0.15/GW-yr as a starting-point value. Using $4 million as the value of the risk to a human life, this figure translates to 0.0068 cents/kWh. Pace University adopts 0.007 cents/kWh as the estimated cost of sudden occupational deaths. Note: Fossil fuel plants also have sudden occupational deaths and these appear to have not been addressed in the study.[12]

Because of long latency periods for illnesses and possibly a "threshold value" for radiation effects, dose-response relationships for radiation are subject to uncertainties, especially for low level exposure. Recent evidence, however, indicates that radiation effects appear to be linear to quite low levels.

Three studies are reviewed for latent occupational mortality due to radiation exposure. Pace University updates these studies with new data from the National Academy of Sciences BEIR III (1989 review) report, which increases the estimate of expected cancer cases per million person-rem to 770. Updating the studies gives a range from 0.15 to 1.95 deaths/GW-yr, translating into cost estimates of 0.0068 to 0.089 cents/kWh, assuming all cancer cases are fatal. Pace University adopts the mid-range figure of 0.07 cents/kWh for latent occupational mortality due to cancer.

One study is reviewed that estimates occupational morbidity at 0.51 to 8.10 illnesses per Gigawatt-year. Multiplying this range by the $400,000 morbidity valuation gives a range of values which translate to 0.0023 to 0.037 cents/kWh. Pace University states that some of this morbidity would be underestimated due to the revised BEIR III dose-response relationships, and this would roughly cancel out any possibility of double counting when illnesses develop into deaths and are counted in the death statistics.

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[12]According to Paul Chernick (personal communication, September 1995), utility consultant for the study, some parts have not been treated uniformly and consistently as some data were not available. The data for fossil fuel plants were not readily available and were left out as the possible error introduced would have been insignificant. For consistency in this work, the $0.00007/kWh can be multiplied by the proportion of electricity supplied by fossil compared to nuclear sources (roughly three times) and added to the total externality cost of electricity, but this would not affect the total because of its insignificance.

Therefore, Pace University adopts a mid-range figure of 0.02 cents/kWh as the starting-point value for occupational morbidity.

For public mortality due to routine operation, one study predicted zero mortality and zero morbidity per Gigawatt-year. Another one estimated 0.020 to 0.025 public deaths per Gigawatt-year. At $4 million per life, the costs range from $80,000 to $100,000 per GW-yr, or 0.0009 to 0.0011 cents/kWh. Pace University asserts that public morbidity and birth defects due to normal operation of nuclear plants should be added to this figure. They therefore adopt 0.001 cents/kWh as the external cost for public mortality for their compilation.

Although a few studies have addressed wildlife and ecosystems, none of them quantified the damage. The value for wildlife is likely to be low though, given that low values, if any at all, are generally assumed for wildlife. Pace University adopts 0.01 cents/kWh as the total for ecosystem and wildlife damage. The authors do not state how they come up with this value.

For property damage due to routine operation, Pace University concludes that there is insufficient data on property value losses to determine the externality cost. Although, looking at the court records, there is some evidence of lost property values due to proximity to a nuclear plant or nuclear fuel transportation route, it appears to be insufficient and not consistent enough for Pace University to assign a figure for this effect. Totaling the costs of routine operation of nuclear plants, Pace University arrives at 0.11 cents/kWh (or $0.0011/kWh). An amount of 0.098 cents/kWh is for human health costs, and 0.01 cents/kWh is for wildlife and ecosystem damage.

External Costs of Accidents

For a variety of reasons, there is much difficulty and uncertainty in estimating the probability of future nuclear accidents, according to the report. Firstly, there are many types of reactor designs, and the operation of these reactors (schedules, procedures, etc.) can change over time. Secondly, there is insufficient data for component and system failure rates, and some events such as the possibility of an earthquake or human error, or how an operator will intervene, do not lend themselves well to prediction. Finally, not all possible accident sequences were modeled, and this will produce accident probabilities that are underestimated by an unknown amount. For the purposes of assigning external costs, Pace University uses the Nuclear Regulatory Commission's (NRC) estimate of the probability of a severe core meltdown accident as 1 chance in 3,333 in one year. This estimate is in the range of Hohmeyer's findings, which were derived from several risk studies for German reactors. Pace University also states that Hohmeyer's estimate for the Chernobyl accident counts as one major accident in 3,000 reactor years.

Pace University cites two studies which use the Chernobyl accident as a case study for the estimation of health costs due to a major accident. One was conducted by Hohmeyer and another by the U.S. Department of Energy (DOE). Hohmeyer's study estimated a worldwide exposure of 240 million person-rem as a result of the Chernobyl accident. Using the revised BEIR relationship of 770 cancers per 1 million person-rem, 185,000 cancers would be expected. Hohmeyer estimated that about half of those cancers would lead to deaths, which predicts 92,500 early deaths. At $4 million per death and $400,000 per illness, the total health cost would be $407 billion. Pace University adds that these costs do not include any non-cancer effects, such as increases in genetic disorders and retardation.

Using the DOE study and the revised BEIR relationships, Pace University estimates $560 billion from cancer fatalities, $18 billion from non-fatal cancers, $280 million from severe mental retardation, and $760 million from genetic disorders, for a total of $579 billion. Given NRC's accident probability, these costs come out to be 2.1 cents/kWh for the Hohmeyer data, and 3.1 cents/kWh for the DOE data. Pace University adopts 2.0 cents/kWh as a starting point value for human health externality costs from a major nuclear accident.

For an estimate of property damage resulting from a major accident, Pace University uses a study assessing the damage to Soviet grain crops as a result of the Chernobyl accident. This damage translates to a range of 0.18 to 0.38 cents/kWh. Pace University states that there are no studies that estimate other property-related costs. Note, however, that property damage costs could be much higher in areas with higher population densities than the Chernobyl area. Altogether, Pace University assigns 2.3 cents/kWh as the starting-point cost for a major nuclear accident, 2.0 cents/kWh for human health costs and 0.3 cents/kWh as the mid-range estimate for property damage costs.

Decommissioning and Waste Disposal Costs

The actual cost of decommissioning a large (commercial) reactor is unknown because as of yet, no large reactor has been decommissioned. Available estimates range from 5-100% of the total cost of the nuclear fuel cycle, according to Pace University's research. Although the NRC requires nuclear facilities to set aside $117 million (in 1989 dollars) for decommissioning costs, many plants are operated without this money being put aside, passing the costs on to future ratepayers. Further, many utility representatives argue that $117 million is insufficient to pay for decommissioning, as recent estimates have been revised upward. For example, actual experience shows that the small Shippingport reactor, a 72 MW light water reactor, cost an estimated $98 million to decommission. (The year the decommissioning costs were incurred is not stated.) Pace University adds that commercial units would cost more than demonstration reactors, since they are more robustly constructed and contain more safety equipment, and they are more radioactive because of longer operation times. Long Island Lighting claims that the Shoreham plant would cost at least $400 million to decommission. And experience with decommissioning the 12.5 MW Japan Power Demonstration Reactor suggests that 1000 MW boiling water reactors will cost about $1.2 billion to decommission. Based on the $1.2 billion cost and the excess cost over the NRC decommissioning guideline, Pace University estimates an adder for decommissioning costs of around 0.65 cents/kWh over a thirty-year plant life to get a "high-end" figure.

The report states further that in 1985, EPRI estimated costs that range from $92 to $170 million (in 1989 dollars) for decommissioning a 1000 MW pressurized water reactor. For a 1100 MW boiling water reactor, Battelle estimated $156 million, and EPRI estimated $113 to $228 for immediate decommissioning and $103 to $106 million for entombment and 100-year surveillance. Because utility estimates of decommissioning costs have been escalating at 19% per year in real terms, Pace University takes 0.50 cents/kWh as a starting point, after presenting a lengthy discussion, summarized above, of the difficulties of making such an estimate. This estimate is the amount in excess of the costs internalized due to the NRC requirements. However, it is debatable whether decommissioning costs should be dealt with by assessing a broad fee across all utilities or by the individual utilities themselves, because many of the cost factors are utility- and plant-specific, and some utilities have put aside more money than others for decommissioning. It seems, however, reasonable to argue that present and not future ratepayers are responsible for these costs, as present ratepayers receive the benefits of nuclear electricity and have some say in the plants' planning and construction. Questions regarding decommissioning policies and costs therefore need to be examined further.

Pace University did not come up with an environmental external cost for high- and low-level waste disposal because of uncertainties in site selection, disposal method, and security and management of the disposal sites. Experience, however, suggests that there will be some environmental externality costs.

Aggregated External Costs for Nuclear Plants

Aggregating Pace University's estimates results in a total external cost of 2.91 cents/kWh, or $0.0291/kWh. The components of this external cost are shown in Table 4.

TABLE 4

PACE UNIVERSITY -- NUCLEAR EXTERNAL COSTS (CENTS/KWH)

Routine Operation	Sudden Occ. Death	0.007	
	Latent Occ. Mortality	0.07	
	Latent Occ. Morbidity	0.02	
	Public Mortality	0.001	
	Wildlife and Ecosystem	0.01	
		Total	0.11
Accident	Human Health	2.0	
	Property Damage	0.3	
		Total	2.3
Decommissioning			0.50
		Grand Total	2.91

Note that this value is only a starting-point value, as the potential externality costs of waste storage and disposal are not included, for reasons of insufficient data. Recall that Pace University limits their discussion to the impacts of plant operation and disposal of waste. The assessment of the environmental and health impacts due to uranium mining, mill tailings, and processing and enrichment is beyond the scope of their study. Nevertheless, it is important that these impacts are assessed. The stages of fuel extraction and processing are very polluting and highly energy intensive. Indeed, Pace University cites a study that estimates that front-end fuel cycle activities account for about 21 times as many occupational deaths due to accidents as nuclear power plant operation. And a recent British study cited by Pace University claims that the nuclear fuel cycle is a major contributor of CO_2 emissions, similar to other fossil fuels. This is probably due to the significant amount of energy (petroleum, electricity, etc.) required in the front-end and fuel extraction and processing activities. Hall, Cleveland, and Kaufman (1992), in their book Energy and Resource Quality: The Ecology of the Economic Process, reviewed seven studies that compared the electrical output generated by nuclear power plants with the fossil energy required as inputs and after standardizing the studies' assumptions, estimated the ratio to be 5±1.5:1. This means that roughly 20% fossil energy equivalent is used for each unit of nuclear energy generated. (These studies assumed that the investment energy was supplied by fossil fuels.) Hall, Cleveland, and Kaufman also state that these studies have not considered the energy required for storing high level wastes and decommissioning. Likewise, it is also important to study the latent health effects of nuclear fuel extraction and processing, as these stages may account for more cancer cases and deaths due to cancer than power production activities at the plant. Also, the costs due to the intake of cooling water need to be determined and incorporated in the total external cost estimate. Therefore, Pace University's estimate of $0.0291/kWh is indeed a conservative starting point value, given present scientific knowledge and the costs that are not included.

Average External Cost for EV Recharging

The OECD (1993) gives figures for the national average marginal mix of power used to recharge electric vehicles, taken from EIA's projections for the year 2000 and detailed in DeLuchi (1991). The figures are: 0.500 will be derived from coal-fired plants, 0.300 from natural gas-fired plants, 0.150 from oil-fired plants, 0.020 from nuclear plants and 0.030 from other sources. The OECD adds that at that time, nearly 25% of all gas-fired generation will be from combustion turbines or combined-cycle turbines, which is a significant proportion of power coming from so-called "new" (i.e. less-polluting) technologies. Pace University's estimate for combined-cycle technology is \$0.011/kWh compared to the existing steam plant cost of \$0.012/kWh. This difference is insignificant and will be ignored. "Other" sources are assumed to be low external cost renewable technologies and therefore these costs are assumed to be zero.

Using the external cost figures for the various generating plants derived earlier and the projected year-2000 national average marginal power mix just given, the average external cost for EV recharging is calculated to be \$0.042/kWh. (Recall that the external cost of batteries is assumed to be insignificant.)

If the residential cost of power for recharging EVs is about \$0.09/kWh, the external cost estimate would be about half of that. If the estimated external cost were included in the price of power, it would result in a significant increase in the cost of recharging EVs. Note also that Pace University considers their external cost estimates to be conservative, in the sense that they underestimate the likely true value, as only part of the damages occurring as a result of the various fuel cycles were included in their analysis. Further, other costs such as energy security and macro-economic costs were not included. However, because of the relative broad scope and comprehensiveness of their study, it is the best-guess estimate available at this time.

Olav Hohmeyer's study, known also to be a relatively comprehensive and recent work on the environmental externality costs of electricity production, will now be evaluated. It will be compared with the Pace University study as much as possible, given the two studies' circumstances and differences.

Hohmeyer Study--Fossil Fuel Plants

Hohmeyer's study is conducted in what was the Federal Republic of Germany (West Germany) at the time of the research. Even though the quantitative results and the estimates of the value of damages cannot be directly employed for the U.S. case, Hohmeyer asserts that his approach is valid for market-oriented economies.

In addition to the environmental effects of electricity generation, Hohmeyer discusses general economic effects and subsidies. Hohmeyer points out that because he does not address the environmental costs of the production of the plant itself, the costs due to the exploration, extraction, and processing of the fuels, and the costs due to disposal of the various wastes, his study is far from being complete. Notwithstanding these gaps, Hohmeyer asserts that the results "should be interpreted as a first systematic overview producing very crude figures which can nevertheless be used as a base for some initial corrective economic policy measures."

Hohmeyer utilizes a different approach for assessing environmental costs from Pace University. Instead of estimating $/lb (or in this case, DM/kg) costs for each of the various important pollutants and then attributing these costs to the various generation technologies based on the amount and types of pollutant emitted, Hohmeyer estimates the percentage of the total damage that is attributable to fossil fuel generation of electricity. Fossil fuel generation includes hard coal, lignite, petroleum, natural gas, and other solid fuels such as peat. (Therefore, from this study one cannot determine the external costs of coal, as opposed to natural gas, for example. Only a cost figure for "fossil fuel" electricity is determined.) To arrive at the required percentage, Hohmeyer uses emissions data and toxicity factors for the various pollutants taken from German government standards called MAK factors. The MAK factor gives the maximum permissible concentration of a pollutant at a place of work and, for Hohmeyer's study, weighs the relative toxicity of pollutants. The annual emissions of the different pollutants attributable to the production of electricity (fossil fuel power plants including combined heat and power stations) compared to the total emissions from all sources is determined. The various pollutants are then multiplied by their respective toxicity factors, to get weighted "damage" potentials. Hohmeyer then arrives at the relative damage factor of 28% for electricity generation from fossil fuels. This factor is applied to total damage estimates of various externalities to get cost estimates for fossil fuel electricity. Note that the relative damage factor of 28% is derived from studies for humans, and the same factor is also used for the case of vegetation, animals, and damages to materials, which may introduce some additional uncertainty to Hohmeyer's analysis. The direction of the bias, however, is unknown at this point.

Damages to Vegetation

Hohmeyer states that studies of air pollution damages on vegetation have been concerned mostly with the economic losses in agriculture and forestry. In Germany, the most visible damage is found in the forests. An assessment of these losses is difficult though, as air pollution effects cannot be easily distinguished from other effects not attributable to air pollution, such as changes in climate. Two studies are reviewed by Hohmeyer. One estimates total damages to agricultural crops and forests to range from 6.5 billion to 9.8 billion Deutsche Mark (DM) per year. This study attempts to include recreational functions of the forest and acidification of the soils. The other study estimates annual damages between 1.7 billion and 9.9 billion DM. Hohmeyer comments that the author is cautious in his estimations and also notes that the trend is in increasing damage costs. Using the first study's figures, the 28% relative damage factor, and adjusting for 1982 values, Hohmeyer estimates a minimum range of damage to vegetation of 1.69 billion to 2.54 billion DM/yr. Hohmeyer asserts this range is a minimum because it does not take into account damages to wild plants.

Damages to Animal Life

Although animal life is also damaged by air pollution, very few quantitative studies exist, making estimates of damages uncertain. Hohmeyer reviews a work which extrapolates the results of an older study to the mid-1980s, resulting in an estimate of 100 million DM per year. He compares this estimate to a German recalculation of an OECD study estimating losses due to SO_2 acidification of Scandinavian surface waters and finds both figures to be in the same order of magnitude. Taking the 100 million DM/yr (1986) figure as the starting point, the damage to animal life, after adjustment for fossil fuel electricity's share and discounting for 1982, is given as approximately 26 million DM/yr. Note that Pace University cited studies which estimate acid deposition effects to recreational fishing in the Adirondacks at about $15 million to $100 million/year. Given that (the former West) Germany is roughly the size of New York state, the figures seem to be of the same order of magnitude.

Damages Affecting Humanity

Hohmeyer cites three studies for estimating health damages. One estimates a range from 2.3 billion to 5.8 billion DM/yr, based on the assumption that air pollution is responsible for 20 to 50% of respiratory diseases. Another study estimates costs to range from 6.8 billion to 27.2 billion DM/yr. A third study gives a range of 1.62 billion to 40.350 billion DM/yr. Hohmeyer states that the first two studies do not address the effects of soil and water pollution, therefore they are probably relatively low estimates for the possible minimum damage. Because the evaluation of health damages is nevertheless highly tentative, Hohmeyer adopts the third study's large range of values as a starting point. Recalculating the total damages for the part fossil fuel electricity is responsible for (using the 28% relative damage factor) gives a range of 0.45 billion to 11.3 billion DM/yr (1982 values). Hohmeyer finds that even the high end figure is well within the range of actual charges that Japanese power plants and industrial firms pay to compensate for the health effects of their SO_2 emissions.

Damages to Materials

Hohmeyer states that heavily polluted industrial areas have been shown to have surface corrosion rates for steel construction about five times as high as areas with relatively clean air. Other materials such as natural stone and works of art are also affected. One study claims material damages due to air pollution at about 2.3 billion DM/yr. Hohmeyer's opinion is that this figure is likely to be low, as historical and cultural properties have not been taken into account at all. Another study gives estimates of 3.2 billion to 4.2 billion DM/yr, also not considering all relevant types of damages. Hohmeyer thus considers a reasonable range to be from 2.3 billion to 4.2 billion DM/yr, which when recalculated for fossil fuel electricity, gives a range of 0.62 billion to 1.09 billion DM/yr (1982 values).

Climate Effects

After giving a discussion on the difficulties and uncertainties in assessing damages due to climatic effects, Hohmeyer cites a study which gives a "first orientation point" cost range of 2.5 billion to 5.0 billion DM to mitigate the costs of global warming. The study estimates the costs to increase the height of coastal defense works (dams, locks, etc.) by one meter due to a rise in sea level. Hohmeyer recalculates this range for the percentage of carbon dioxide put out by fossil fuel electric plants (about 35%) and assumes a period of 50 years for the climatic change to occur. Average annual costs of 20 million to 40 million DM (1982) result.

Aggregated External Cost Estimate for Environmental Damages

Summing the damage estimates reviewed above results in a total environmental cost range of 2.81 billion to 15.00 billion DM per year. Hohmeyer compares this range with a willingness-to-pay study conducted in Berlin which estimates 12.47 billion DM for fossil fuel electricity's share. This estimate is only used as a point of comparison, as the method is acknowledged to be unsound for the types of damages studied. Hohmeyer considers the 2.81 billion to 15.00 billion DM/yr values as the minimum damage caused by the emission of pollutants by fossil-fuel burning power plants, because assumptions have been chosen to be conservative. Further, the damages due to the front-end of the fuel cycle have not been considered in Hohmeyer's analysis. Dividing the range for the annual external cost by the annual electrical output for (former West) Germany gives figures on the basis of cost per kWh of electricity produced. The external cost range for fossil fuel electricity is then 0.011 to 0.061 DM/kWh. Converting to U.S. dollars using the current (1994) exchange rate ($1 = 1.65 DM) for a rough comparison, this turns out to be $0.007/kWh to $0.037/kWh. Although not very meaningful, one can compare these numbers to Pace University's external cost estimates for fossil fuel generation: $0.063/kWh for coal, $0.045/kWh for oil, and $0.012/kWh for gas-fired electricity generation. Only a rough order-of-magnitude comparison is possible here as many factors, which are different for the two countries, come into play. Some of these include the different economies, costs-of-living, population densities, geography, generation technologies and proportions thereof, pollution control technologies, different levels of government support, etc. What is noteworthy though is that the final estimates are not all that different, lending some degree of credibility to them.

Olav Hohmeyer's study for estimating the external costs of electricity from nuclear power plants will be discussed next.

Hohmeyer Study--Nuclear Power Plants

After giving a background discussion on nuclear energy, its possible effects, and the uncertainties involved in estimating damages, Hohmeyer presents a rather thorough exercise in the estimation of the external costs of nuclear electricity. He begins by stating that because of insufficient studies that quantify environmental damages due to the routine operation of nuclear power plants, it seems reasonable for a first analysis to quantify the possible effects of a large nuclear accident such as Chernobyl. Hohmeyer comments that although some experts argue that the Chernobyl accident could not result in health effects in Germany, a recent study shows that there have been a higher number of cancer patients and greater incidence of genetic damage to embryos.

Hohmeyer estimates health damages resulting from the Chernobyl accident and uses this figure as a starting point for the effects of nuclear power on health. Hohmeyer uses a rather low value for the worth of a human life--1 million DM for a cancer death and 500,000 DM for morbidity, which he estimates as the loss of economic productivity due to cancer. For comparison, 1 million DM is roughly about $610,000. Hohmeyer states that because this value does not take into account the enormous costs for health care and the psycho-social costs of cancer, his calculation will only give a rough estimate of the minimal economic damages caused by a nuclear accident.

To estimate these damages, the following must be known: the number of incidents of cancer per unit of radiation exposure, the probability of the occurrence of an accident leading to release of core material, the severity of the accident, i.e. how much nuclear inventory will be released (assumed by Hohmeyer to be between 1% and 50%), and the population densities of the areas affected.

Studies estimating the number of cancer occurrences per million person rem give figures that range between 200 and 7,400. Hohmeyer uses the range 200 to 3,700 for his calculation. Roughly half of cancer incidents are typically assumed to be fatal, according to his literature search. As a result of the Chernobyl accident, a total of 240 million person rem of radiation was estimated to be released, about 12 million person rem of which was assumed to reach West Germany. For the Chernobyl accident, only about 4% of the radioactive inventory was actually released, as melting of the core was prevented. The probability of a nuclear accident of sufficient magnitude to release substantial nuclear inventory ranges from 2,000 to 20,000 operation years. The Chernobyl accident happened after about 3,000 operation years worldwide, and a number of prior accidents almost resulted in excursion of nuclear inventory. These data are obtained from Hohmeyer's research and calculations.

Hohmeyer then calculates high- and low-end cost estimates for a nuclear accident. For a possible low-end estimate, Hohmeyer assumes release of 1% of the inventory and a population density half that of the Chernobyl area. For the high-end estimate, a 12.5% release and population density 10 times that of the Chernobyl area is assumed (approximating Germany's population density). Factoring in the range for cancer occurrences (200 to 3,700) results in an overall estimate of between 6,000 and 110 million cancer occurrences. The economic damages then range from 4.5 billion to 83,000 billion DM. These costs translate to a minimum of 0.00003 DM/kWh and a maximum of 5.55 DM/kWh, a difference of a factor of 185,000. This exercise is conducted probably to show the possible variations involved.

For a more practical range, Hohmeyer considers the Chernobyl accident and assumes 1,000 cancer incidents per million person rem, 1/3000 per year accident probability, and the Chernobyl area's population density. From these assumptions, economic damages of 0.012 DM/kWh result. Next, he considers the accident in Germany, where the population density is 10 times as great and takes into account the probability range for such an accident, arriving at the economic damage of 0.012 to 0.12 DM/kWh. Hohmeyer adopts 0.012 to 0.12 DM/kWh as a rather probable minimal damage range (a starting point) for such accidents in Germany. Health care costs and psycho-social damages have not been estimated. Further, several other processes in the nuclear fuel cycle have not been considered at all: uranium mining, processing, and transportation, effects of routine operation of nuclear plants, reprocessing of radioactive waste, waste disposal, and decommissioning of nuclear power plants, which Hohmeyer argues need to be studied and taken into account in the future.

For a very rough comparison, Hohmeyer's 0.012 to 0.12 DM/kWh are converted to U.S. dollars using the current (1994) exchange rate $1 = 1.65 DM. Hohmeyer's nuclear energy external costs then range from 0.73 to 7.3 cents/kWh. Pace University's external cost estimation for nuclear electricity of 2.91 cents/kWh is well within Hohmeyer's range. Since Germany's population density is greater than the U.S.'s and population density is a major determining factor for the environmental costs of nuclear power, it would be safe to say that Hohmeyer's "high-end" estimate is probably more accurate than the "low-end" estimate as a "starting point" external cost value for Germany.

The following external costs were included in Hohmeyer's study but not in the study completed by Pace University. They are briefly reviewed here for completeness, as including them in any comprehensive study on the external costs of energy may be useful.

Hohmeyer Study--Miscellaneous Economic Effects

Depletion Costs

According to Hohmeyer, when the costs of long-term scarcity to society are ignored (e.g., for depletable natural resources that are priced according to their extraction costs), external effects occur. The objective, then, is to make possible an optimum intertemporal allocation of depletable resources. Hohmeyer discusses depletion surcharges for electricity from fossil fuels and nuclear energy. None of the other external cost studies address this effect. This effect should be studied and incorporated in future comprehensive external cost analyses.

Public Subsidies

Because a discussion of public subsidies is outside the scope of this work (especially when it's for a foreign country), only a listing of the possible types of subsidies to be aware of and include in external cost studies will be given. Hohmeyer includes the following types of subsidies and government programs in his assessment: forestry expenditure programs (e.g. the liming of forests due to the effects of air pollution), public liability for civil nuclear accidents, public expenditure for environmental administration and control (fees do not often cover the costs of control measures taken by the government, also air monitoring costs for monitoring air pollution and radioactivity), and public R&D transfers.

In the following chapter, an attempt is made to estimate the external costs of natural gas as an automotive fuel.

CHAPTER VII

External Cost of Natural Gas as a Fuel for Light-Duty Vehicles

Comprehensive external cost studies for the use of natural gas as a fuel for vehicles have not as yet been done. This is not surprising, as there are very few CNG-fueled vehicles relative to gasoline-fueled vehicles on the road in the U.S. However, because natural gas as a heating fuel has been around for quite a while, and because quite a few CNG-powered vehicles have been either built through conversion or built at the factory and emissions-tested, enough information is available to at least make preliminary external cost estimates relative to petroleum. Obviously, these estimates will be subject to confirmation with further studies, but then so are estimates for gasoline-powered vehicles and battery-powered electric vehicles. Nevertheless, a rough estimate of external costs for NGVs compared with external costs of gasoline-powered vehicles is attempted.

Before attempting the preliminary external cost estimate, it is important to note that emissions only will be evaluated, as external cost studies for energy security, water pollution, and land pollution impacts from the natural gas fuel cycle are scarce. However, these costs are assumed to be low. DeLuchi, Sperling, and Johnston (1987), for example, state that the external costs to the economy of a disruption in imported natural gas are assumed to be zero, because of the small quantities of gas that are imported from Canada relative to domestic gas, and also because the possibility of a disruption in pipeline imports is very low. Besides emissions, DeLuchi, Sperling, and Johnston state that the major environmental impacts of natural gas production and distribution are the clearing of land required for pipelines that are above ground, and the noise and visual disturbance from pipeline compressors. However, these would be minor compared to the environmental impacts of the distribution of gasoline by trucks. A publication by the Organization for Economic Cooperation and Development (1993) also reports that in general, the production of natural gas is environmentally benign. The OECD further states that the main environmental concerns in the production and transmission of natural gas are the impacts of pipelines on the ground, the leakage of methane gas, and the sulfur emitted by gas processing plants, if these are not minimized. These effects, nevertheless, need to be addressed in future research so that the full impacts of natural gas production, distribution, and use could be estimated. For the purpose of this evaluation, it is sufficient to note that the external costs of natural gas that are not estimated here are very likely to be smaller than those for petroleum.

Darrow Study--Emissions Analysis

In Light Duty Vehicles Full Fuel Cycle Emissions Analysis (1994), Kenneth G. Darrow of Energy International, Inc. conducts a study for the Gas Research Institute and analyses full fuel cycle emissions of alternative automotive fuels, including gasoline and natural gas. Although the report is not "ideal" for the purpose of this work in that it does not address externalities other than emissions, the external cost analyses for petroleum and electricity indicated that emissions seem to be the most significant externalities anyway (perhaps besides energy security costs, which are also significant for petroleum.) Therefore, this analysis will tend to be conservative in that it will overestimate the external cost of natural gas as compared to petroleum.

Data from three other studies, the Environmental Protection Agency's (1990) Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel , and the American Gas Association's (AGA) Natural Gas and Electric Vehicles: An Economic and Environmental Comparison with Gasoline Vehicles (1991), and Analysis of the Economic and Environmental Effects of Natural Gas as an Alternative Fuel (1989) will be compared with Darrow's analysis.

In his study, Darrow examines the total emissions resulting from the full fuel cycle of petroleum and natural gas. The full fuel cycle consists of fuel extraction, processing, transportation, and end use in vehicles. To get front-end fuel cycle emissions (those emissions occurring before end use), Darrow collects fuel cycle energy use data from published sources, identifies technologies and emissions characteristics currently available and those projected to be available for the year 2000 for each step of the entire front-end fuel cycle, and calculates total emissions for each fuel step. The emissions for each step are then totaled and added to values obtained from vehicle emissions tests to yield full fuel cycle emissions.

The natural gas vehicle tested is the 1994 production Chrysler natural gas-powered minivan, which also has a gasoline-powered counterpart. This natural gas vehicle has received ultra-low emissions vehicle (ULEV) certification in California. Actual 50,000 mile certification results for emissions from two CNG-powered minivans were used in the analysis. These data are compared with Federal Tier I emissions standards for gasoline. Note: Data from two similar CNG-powered minivans is hardly sufficient to draw any concrete conclusions. Therefore, the studies and the results presented here are to be regarded as preliminary until sufficient studies can be done to obtain statistically significant results. Also, precautions should be taken so that the emissions-testing equipment itself and the setup of the emissions test can introduce minimal errors. Emissions data will be reproducible only if the test variables, for example, the temperature and the quantity of fuel burned, are carefully controlled.

For the petroleum fuel cycle, emissions from the various front-end fuel cycle steps were estimated. These emitting processes included: engine-driven pumps and compressors for pumping oil at the wellhead, refinery operations, distribution processes, and leakage and vapor releases from all stages of the fuel cycle, including releases at the wellhead, refinery, tank storage, and retail gasoline distribution. (The releases from tank storage addressed here are vapor releases, not seepage due to leaky tanks which causes water and soil pollution.) Note that oil spills and solid wastes are not considered in this analysis.

For the front-end of the natural gas fuel cycle, total combustion process emissions and nonmethane fugitive emissions are estimated. These processes include: fuel used on natural gas production leases (used mostly in gas engines for the compression of natural gas), fuel used in plants that separate natural gas liquids and other component gases from the methane, some gas that is flared that is attributable to nonassociated gas production, fuel used by compressor stations for gas transmission, and energy (mostly electric) used to compress natural gas to vehicle storage pressures of 3,000 psi.

For the vehicle emissions analysis, certain simplifying assumptions were made by Darrow: 1) It is assumed that the vehicle fuel efficiency for the two fuels is the same. Fuel efficiency in actuality may be different due to the slightly higher weight of the natural gas vehicle (which would decrease the efficiency) and the higher octane rating of the natural gas (which would tend to increase the efficiency). Optimization of the fuel to the engine would also tend to increase the natural gas vehicle fuel efficiency. 2) It is also assumed that the average vehicle usage is 31.1 miles per day, including one diurnal and three hot soaks, which results in evaporative emissions for gasoline in addition to the emissions from vehicle operation. Evaporative emissions for natural gas are assumed to be zero. CARB (1994) also reports that NGVs have no fuel evaporative, running loss, and marketing emissions.

Full fuel cycle emissions can then be determined and compared. Darrow calculates total emissions for ROG (reactive organic gases), CO, NO_x, SO_x, PM10, and CO_2 equivalent for gasoline and natural gas. The total emissions for the two fuels are calculated for the current (1994) case and for the year 2000.

It should be noted here that most of the emissions tests done so far on NGVs were performed on either converted or dual-fueled vehicles, which are not optimized for the use of compressed natural gas as a vehicle fuel. NGVs tested by the AGA (reviewed in this section) are not dedicated. It is expected that dedicated and optimized NGVs should achieve higher emissions standards and also improved energy efficiency compared with converted or dual-fuel vehicles. Improved energy efficiency for dedicated NGVs compared with gasoline vehicles is also expected, according to the 1989 AGA report.

For the current time period (1994), Darrow calculates ROG full fuel cycle emissions to be 0.698 grams per mile (g/mile) for gasoline and 0.116 g/mile for natural gas, which represents an 83.4% reduction in ROG for natural gas. Fewer ROG emissions would result in less tropospheric ozone pollution, which would be a significant improvement for the most polluted urban areas in the country. This figure can be compared to the AGA (1991) estimate of 85% reduction of nonmethane hydrocarbons, the AGA (1989) estimate of an 87% to 90% reduction, and the EPA's (1990) projection of 80% to 93% reduction for dedicated natural gas vehicles. Note: The 1991 AGA report considers full fuel cycle emissions while the 1989 AGA and the 1990 EPA reports address vehicle emissions only. For the year 2000 case, natural gas vehicles are projected to allow an 83.8% reduction in ROG emissions compared to the gasoline vehicle available at that time, according to Darrow's analysis.

For CO emissions, Darrow calculates 3.480 g/mile for gasoline and 0.461 g/mile for natural gas. This represents an 86.8% reduction in CO emissions when natural gas vehicles are used. The AGA (1991) estimates a 90% reduction, and the 1989 report gives an 82% to 90% reduction. EPA (1990) reports a 99% reduction in CO emissions for the two 1984 dedicated CNG-powered Ford Rangers tested for their study. At the time of the

EPA report, the 1984 Ford Ranger was the only dedicated NGV available. For the situation in the year 2000, Darrow projects an 86.7% decrease in CO emissions for natural gas as compared with gasoline.

For NO_x emissions, 0.626 g/mile for gasoline and 0.537 g/mile for natural gas is calculated, resulting in a 14.2% decrease for natural gas. This is rather surprising, as increases in NO_x emissions were expected for natural gas. The 1991 AGA report estimates a 14% reduction, and the 1989 report states that for optimized dedicated natural gas vehicles, it appears possible to reduce NO_x emissions by about 30%, while at the same time reducing both ROG and CO emissions by over 90%. The EPA report gives test data for the 1984 CNG-powered Ford Ranger showing an 82% increase in NO_x emissions compared with gasoline. In general, there are tradeoffs between reductions in CO and NO_x emissions. Additional dedicated NGVs with optimal engine design (i.e. mature state of the technology) need to be tested because matching the design of the engine to the fuel is critical. For the year 2000 case, Darrow predicts a 46.7% reduction in NO_x emissions for the NGV. This significant future reduction in NO_x emissions could be because of optimization of the engine and emissions control equipment to the natural gas.

For emissions of SO_x, 0.044 g/mile for gasoline and 0.299 g/mile for natural gas is determined. This represents an increase of 580% in SO_x emissions, all of which arise from the front end of the fuel cycle. It is interesting that the 1991 AGA study, which also evaluates full fuel cycle emissions, reports virtually no SO_2 (less than 0.005 g/mile) for natural gas and 0.16 g/mile for gasoline. Checking the Pace University study for emissions for natural gas- and oil-fired electricity generation shows that SO_2 emissions/kWh from oil-fired generation are about three orders of magnitude higher. Even though these are combustion emissions from the generation of electricity and Pace University does not address front-end fuel cycle effects, the data suggest that front-end emissions for natural gas could also be low. However, a report by the OECD (1993) suggests that sulfur emissions from gas processing plants could be a concern if these are not minimized. Therefore further study of SO_x emissions for the front end of the fuel cycle should be conducted to clear up these discrepancies. SO_x emissions are not tested in the 1989 AGA and the 1990 EPA analyses, as gasoline-powered and CNG-powered vehicles do not emit SO_x. For the year 2000 situation, Darrow estimates an increase in SO_x for natural gas of

140% over that of gasoline. The significant decrease could be a result of improved technology or practices that reduce the amount of sulfur emitted during gas processing.

For particulate matter (PM10), Darrow gives estimates of 0.013 g/mile for gasoline and 0.006 g/mile for natural gas, which results in a 53.8% decrease in PM10 for natural gas. Again, all of the PM10 results from the front end of the fuel cycle. The 1991 AGA analysis does not consider particulate matter, and neither do the other two studies because this pollutant is virtually absent in vehicle emissions. For the year 2000, Darrow projects that the relative PM10 emissions for gasoline and natural gas will remain about the same as the current situation.

For CO_2 and other global warming gases, Darrow estimates "CO_2 equivalent" emissions of 468.4 g/mile for gasoline and 395.9 g/mile for natural gas. This results in a 15.5% decrease in total global warming impact for the natural gas compared with gasoline. Darrow assumes global warming potential factors of 1 for CO_2, 11 for CH_4, and 270 for N_2O. Darrow claims that these numbers are accepted global warming factors. Using a global warming potential (on a mass basis) of 21 for CH_4, the 1991 AGA analysis reports a net reduction of global warming impact of approximately 21% for natural gas. The AGA report does not consider the impact of N_2O emissions, which favors gasoline in this analysis, according to Darrow's data. The 1989 AGA report gives global warming impact reductions of 25% for natural gas. This report uses the factor 30 as the relative "potency" of methane as a greenhouse gas. AGA states that 30 is probably high. The EPA report states that their analysis is incomplete in that it does not include the front end fuel cycle global warming emissions. The factors used for their vehicle emissions are 65 for CH_4 and 300 for N_2O. When using these factors, EPA estimates that the global warming impact for both gasoline and natural gas is roughly the same. The EPA report also shows a sensitivity analysis, testing the sensitivity of the results to three different global warming potential factors for methane: 16, 65, and 116. Apparently, this factor may still be an area of controversy. Darrow projects an 18.5% decrease in global warming impact for natural gas compared with gasoline for the technology situation in the year 2000.

The 1991 AGA report and the EPA reports also address air toxics emissions. Both reports state that the impact of air toxics emissions (benzene, toluene, polycyclic organics) will be reduced by about 90% compared to gasoline. Since these pollutants are either known or probable human carcinogens, the advantage of natural gas here could be significant. Emissions of the air toxin formaldehyde are considered approximately the same for gasoline and natural gas. Darrow does not include air toxins in his analysis.

Darrow concludes his analysis with a discussion that stresses the importance of including full fuel cycle emissions when considering alternative fuels. (Darrow's analysis also includes electric vehicles, and he concludes that if full fuel cycle emissions are considered, the California-certified NGV minivan can be considered equivalent to an electric vehicle, and therefore should be considered a zero-emission vehicle under the California Low Emission Vehicle Program.)

Estimation of External Costs of Emissions: Natural Gas vs. Gasoline

The assumptions in this external cost estimation are: one gallon of gasoline has the net energy content of 114,132 BTU (EPA 1990), giving one gallon of gasoline equivalent to 1.14 therms of natural gas. Also, the energy efficiency for the alternative fuels (natural gas and gasoline) is assumed to be equal, and the vehicle energy efficiency is 22 miles per gallon for the Chrysler minivan. Using Darrow's current emissions data (grams/mile for each pollutant), and using $/gram pollutant figures compiled and selected by Miller in his external cost analysis of petroleum-fueled vehicles, a very preliminary estimate of external costs of emissions for natural gas compared to gasoline can be estimated. The cost estimates are given per gallon of gasoline equivalent. Note: Where there is a range for Miller's $/gram figures, the lower end figure is used. The $/gram figures used for this analysis, derived from Miller, are shown in Table 5.

TABLE 5

POLLUTANT COSTS, DERIVED FROM MILLER ET AL. ($/GRAM)

ROG	0.0022
CO	0.001
NO_X	0.00064
SO_X	0.001
PM10	0.0036
CO_2	0.00006

For ROG, the cost calculation is $0.0338/gallon for gasoline and $0.0056/gallon equivalent for natural gas (see Table 6). For CO, it is $0.077/gal. for gasoline and $0.010/gal. equiv. for natural gas. For NO_x, the estimate is 0.009/gal. for gasoline and $0.008/gal. equiv. for natural gas. The PM10 estimate is $0.001/gal. for gasoline and $0.0005/gal. equiv. for natural gas. For the CO_2 equivalent, calculation results in $0.618/gal. for gasoline and $0.523/gal. equiv. for natural gas. SO_x is not added here because of the gross inconsistencies in the data. However, because the $/gm cost for SO_x is not insignificant, and because the OECD (1993) reports that the sulfur emissions from natural gas processing plants are a concern if not minimized, it needs to be further researched and included for a more complete analysis. Also not included here is the external cost of air toxics emissions, which would be smaller for natural gas. From these, the total external cost for emissions is calculated to be $0.739/gal. for gasoline and $0.547/gal. equiv. for natural gas. These external costs can be corroborated with DeLuchi, Sperling, and Johnston's (1987) assertion that optimized natural gas vehicles would cause about 50 to 80% of the damage of gasoline vehicles.

TABLE 6

CALCULATED EMISSIONS COST FOR GASOLINE AND NATURAL GAS

Pollutant	Gasoline ($/gallon)	Natural Gas ($/gallon equiv.)
ROG	0.0338	0.0056
CO	0.077	0.010
NO_x	0.009	0.008
PM10	0.001	0.0005
CO_2	0.618	0.523
SO_x	N/A	N/A
Total	0.739	0.547

It is important to note again that these external costs are based on emissions figures from one study, with one other study confirming the relative full fuel cycle emissions. Hence, further work will need to be done to verify these numbers when additional data from dedicated and optimized natural gas vehicles will be available. Also, research should be done to verify the low external costs of the other environmental and societal considerations of the use of natural gas, with particular attention being paid to the front-end impacts of sulfur oxide pollution.

The final fuel to be evaluated for its external cost is solar hydrogen, which is the topic for the next chapter.

CHAPTER VIII

External Costs of Solar Hydrogen-Powered Fuel Cell Vehicles

Because solar-Hydrogen powered fuel-cell vehicles are not yet available, studies have not yet thoroughly explored the range of environmental impacts and respective external costs that could result. Given the large uncertainties associated with an immature technology, this can make assessments difficult, but not, however, impossible. As policy decisions must rest on a critical evaluation of the social costs of new technologies compared with the conventional alternatives, it is important to conduct preliminary analyses.

Using the scenario formed in the technology assessment section of this work, an attempt is made to estimate, at least roughly, the possible external costs. Required for this estimation are the external costs of the production of electricity from photovoltaic panels (which will drive the electrolysis process), estimates of the costs of environmental impacts of the production of hydrogen through electrolysis, the distribution of the hydrogen fuel, the production of fuel cells, if any, and estimates of any other relevant costs, such as subsidies to the photovoltaic industry.

The environmental impacts of the electrolysis process are assumed to be low, and so is the production of fuel cells at this time. In any case, the impacts of the production of hydrogen through the electrolysis of water would seem to be lower than the production and processing of fossil fuels, given that there would be no significant emissions. A phone conversation with Joan Ogden (1994) of the Center for Energy and Environmental Studies at Princeton University confirms this assumption. Joan Ogden explained that although there would be chemicals such as potassium hydroxide used in the electrolytic solution, the impacts of electrolysis would be quite small. Some cooling water would be needed, but the quantity would be minuscule compared to the cooling water needed by a fossil- or nuclear-generation plant, especially since the cooling water system for the electrolysis plant would generally be closed-loop and would recycle its water. The toxic wastes produced in the manufacture of PEM fuel cells would also need to be assessed, but Ogden feels these are considered to be less than or comparable to the wastes produced by the manufacture of the conventional alternative.

A report published by the OECD (1993) conveys that the production and distribution of hydrogen could be essentially pollution-free if hydrogen were made from water using a clean, renewable source of power such as solar electricity, which is the scenario assumed. However, it would seem reasonable that, at first glance, hydrogen distributed through pipelines would have similar land-use impacts as pipeline distribution of natural gas. Referring back to the natural gas section shows that analysts consider these impacts smaller than the impacts of the distribution of gasoline. However, these impacts still need to be assessed and accounted for, including any dissimilarities in handling due to the different properties of the two gases. The question of occupational and consumer safety of the use of hydrogen gas would also need to be addressed. Currently, the scientific consensus is that, although the hazards of hydrogen are different from petroleum and other fossil fuels, they are not necessarily greater.

Finally, the environmental impacts and the external costs of electricity from photovoltaics need to be assessed. Two studies, one conducted by Pace University and the other by Hohmeyer, review these costs. They are discussed below. Other possible environmental impacts are assumed at this time to be low. Technologies and situations may change, however, so these assumptions would need to be reassessed once the scenario is more determined.

Pace University Study

Pace University researchers find that the environmental impacts for photovoltaic (PV) electricity include front-end impacts associated with the production of photovoltaic arrays, the land and maintenance requirements during operation, and decommissioning impacts. Because front-end impacts are excluded in their analysis of fossil-fuel and nuclear electricity, PV industry front-end impacts (e.g. the manufacturing of solar cells) are also excluded, except for a qualitative description of possible impacts.

The manufacturing of thin film silicon solar cells exposes workers to hazardous gases and other chemicals that usually have immediate health effects after an acute exposure. The analysts report that industry data are not yet sufficient to quantify probabilities for worker exposure and their subsequent health effects, and therefore, no quantitative results are given. Also, it has been found that following basic industrial safety practices allows the safe handling of hazardous materials. (These hazardous materials, such as organic solvents and heavy metals, are routinely used in the manufacture of computer chips.) Pace University reiterates that these front-end costs must be compared with front-end costs of other electricity generating technologies, for a thorough comparison of all the external effects.

However, the front-end costs that affect the general population could be significant, as the computer chip industry in Silicon Valley has found. In the early 1980's, soil and groundwater at over 200 sites was found to be contaminated by volatile organic compounds used as solvents and metal degreasers. Twenty-eight of these sites were either listed or proposed to be listed on the Federal EPA National Priorities List for Superfund, and 19 public water supply wells and 50 private wells were found to be contaminated at these sites (California Environmental Protection Agency 1993). Much of this contamination was the result of leaking underground tanks. The cost and the effort put into cleanup has encouraged industry to adopt manufacturing practices which eliminate or reduce the use of organic solvents such that chemical releases between 1987 and 1990 are down 52.7% in the Santa Clara Valley compared to 33.5% across California and 31.3% across the U.S. (California Environmental Protection Agency 1993). In The Social Costs of Solar Energy: A Study of Photovoltaic Systems, Neff (1981) states that the greatest and most direct risk appears to result from the release of toxic or carcinogenic materials to the workplace or the environment. Therefore, the front-end effects that the photovoltaic industry could have on the environment as well as on the workplace needs to be assessed in the future, along with the front-end costs of the fossil fuel and nuclear industries. Such risks can be greatly reduced if the photovoltaic industry devotes enough attention to them from the onset and learns from the experience of other industries.

During the operation of central solar facilities, land use impacts result. And where land use impacts are negligible for decentralized, roof-top systems, the hazards of roof-top maintenance become the main issue. Pace University reviews two studies that evaluate these externalities and others associated with photovoltaic generators. The Bonneville Power Administration/ECO study found no significant environmental effects from which external costs could be derived. Hohmeyer's study resulted in an average external cost of about 0.2 cents/kWh, for the case of former West Germany.

The operation of photovoltaic facilities results in environmental impacts related to land use. Water, air, and noise impacts (emissions, wastes, etc.) are considered minimal or nonexistent at this stage and so are not discussed further. (Water requirements are limited to periodic cleaning of the arrays and personal use by the staff.) According to three sources cited in the Pace University review, photovoltaic central station facilities may require between about 230 and 1,400 acres for generating 100 MW of electricity. However, another study cited claims that this land requirement is similar to that of a coal production and combustion facility, when compared on a kilowatt-hour basis.

Pace University reviews Hohmeyer's study, which quantifies land use externalities for central station plants at 0.44 cents/kWh. Hohmeyer assumes that the opportunity costs of land use not covered in the purchase price are about 10% of the real estate price. Hohmeyer adds that this assumption may overestimate the external costs by a great deal, but that the approach of his analysis is to make "assumptions to the disadvantage of renewable energy." Hohmeyer's figure for real estate prices, however, is not valid for the U.S., as real estate prices are considerably higher for the former West Germany. Instead of using Hohmeyer's figure of $66,000/acre (converted from DM), Pace University substitutes $5,000/acre, a more reasonable figure for the acreage that might be used for a solar plant in the U.S. After recalculation, Pace University comes up with an external cost value for central station PV land externalities of 0.04 cents/kWh. Pace University also states that some of this land externality cost should be considered "front-end," as front-end land costs for fossil fuel and nuclear electricity are significant and have not been included in their analysis.

For decentralized installations, the major impact is the possible hazard to workers during installation, maintenance, and removal of rooftop systems, in the form of possible electric shocks or falling off the roof. Due to the risk of these possible accidents, Hohmeyer derives a value of 0.004 cents/kWh. Since it seems reasonable that the risk of electric shock can be significantly reduced by a good engineering design, and falling reduced by the following of simple safety guidelines, even this external cost may be considered high.

Assuming that half of PV electricity will be produced by decentralized installations and half by central station plants, an average external cost of 0.022 cents/kWh is obtained.

Pace University does not discuss the environmental impacts of decommissioning silicon solar cell arrays, but these are likely to be low compared to the decommissioning costs of nuclear and perhaps fossil fuel plants as well. Nevertheless, research on the costs and impacts of solar plant decommissioning must be done to include these costs in the external cost aggregation.

Hohmeyer Study

Hohmeyer discusses the impacts of photovoltaic solar installations on land use, the possible risks to maintenance workers from rooftop installations, and the risks to humans and the environment from the production and disposal of solar cells.

For silicon solar cell technologies, Hohmeyer's assertion is that manufacturing and production of even large scale systems will not cause any greater environmental problems than the production of conventional energy systems. The risks associated with silicon solar cells are concentrated in the fabrication process and are fairly easy to control, as is demonstrated in the semiconductor industry. And the disposal of silicon solar cells should not create significant environmental concerns. Because cost figures are not available for these front-end and disposal effects, they cannot be included in his analysis. Hohmeyer states that front-end and disposal costs are areas that need to be addressed for all energy technologies, since figures are not included for conventional energy as well.

For the operation of decentralized PV installations, Hohmeyer reviews a study that estimates accident risks for maintenance workers and calculates an external cost of 0.00007 DM/kWh (1982 value). Recall that Hohmeyer uses lost production values as the value for the risk to a human life. But even when this value is multiplied 5 or even 10 times, the external cost for accidents is still very low.

For central station solar installations, the external cost is probably dominated by the lost opportunity costs of the land use that is not covered by real estate prices. However, lost opportunity costs affect conventional energy systems as well, and a thorough analysis would take this into account for all energy systems. Hohmeyer, using Germany's real estate prices and the assumption that 10% of the real estate price is the lost opportunity cost, assesses an external cost figure of 0.0044 DM/kWh.

Hohmeyer also estimates a value for the overall external economic effects, in terms of effects on savings, imports, gross value added, and employment, and calculates a positive effect (a net benefit) of between 0.0296 to 0.0665 DM (1982)/kWh. Further discussion of external economic effects is beyond the scope of this work, especially since these are not addressed by Pace University. Note however that in Hohmeyer's analysis, the inclusion of external economic effects would result in an overall (positive) net benefit for solar electricity.

Finally, Hohmeyer addresses public expenditures for solar electricity, a topic also not covered by Pace University. Although the figures for public subsidies would not have much meaning for the U.S. case, it is interesting to note that Hohmeyer's estimation shows that solar electricity received, per kilowatt hour of electricity produced, approximately one-third of what was received by the nuclear electricity industry. This figure includes Hohmeyer's estimate of what would be needed in future R&D transfers to bring photovoltaic electricity to market maturity.

The external costs of solar hydrogen-powered fuel cell vehicles, when and if they will be available in the future, appear to be significantly smaller than the external costs of the other vehicle technologies considered in this work. As stated earlier in our review of the alternative technologies, solar hydrogen-powered fuel cell vehicles are very much in the concept stage of development. Presently, it is the technology farthest away from commercial availability. However, this doesn't exclude solar FCVs from being the preferred technology several years down the line. Because fuel cells for use in automobiles, for example, are very much in the early stages of research compared to other technologies, there is more of a prospect for unforeseen breakthroughs to occur that may, coupled with environmental advantages, result in FCVs being very attractive.

Summary of External Costs for the Alternatives

From the material presented, a table is constructed for a comparison of the alternative fuels. This summary table (Table 7) gives the alternative fuel, the study reviewed, the external cost that resulted from the study, and an external cost per mile, calculated so that a direct comparison can be made between the fuels. To obtain external costs per mile, the external cost per gallon or per kilowatt-hour is converted by factoring in average vehicle efficiencies for the different technologies. Because actual average light-duty vehicle efficiencies are not available, assumptions are made (see footnotes to the table) which will have to be verified as data becomes available.

Examination of the table shows that the external costs are highest for petroleum, even if MacKenzie's more conservatively-derived external costs are given more weight than Miller's. They are not insignificant for EV recharging (year 2000 national marginal mix) and for natural gas. Nevertheless, it appears that EV recharging and natural gas would be a substantial improvement over petroleum. The only option that has external costs that are very low is hydrogen fuel derived from solar electricity. However, this is the option that is furthest away from commercial availability.

TABLE 7

TOTAL EXTERNAL COST ESTIMATES BY FUEL

Fuel	Study	External Cost	External Cost per Mile
Petroleum	MacKenzie	$ 0.46/gallon	$ 0.017[13]
	Miller	$ 1.59 - 3.60/gallon	$ 0.058 - 0.13
Electricity (nat'l mar. mix)	Pace University	$ 0.042/kWh	$ 0.011[14]
	Hohmeyer	N/A	N/A
Natural Gas	Darrow	$ 0.547/gal. equiv. compared to $ 0.739/gal. for emissions only	$ 0.020 compared to $ 0.027 for emissions only[15]
Solar-derived Hydrogen	Pace University	$ 0.00022/kWh	$ 0.0002[16]
	Hohmeyer	N/A, but calculates a small net benefit for Germany	N/A

[13]Average fuel efficiency for gasoline-powered light-duty vehicles assumed to be 27.5 mpg, which actually was never once achieved, according to Nadis and MacKenzie (1993). Marc Ross (1989) gives the new car in-use fuel economy to be 22 mpg.

[14]Electric vehicle efficiency assumed to be 0.25 kWh/mile (Hwang and others 1994)

[15]Fuel efficiency for CNG-powered vehicles assumed to be 27.5 mpg equivalent. CNG uses its energy 5-10% more efficiently than gasoline, which roughly cancels out the slight increase in weight for CNG vehicles (appx. 180 pounds for a Crown Victoria) (Ford Corporation brochure).

[16]1.07 kWh/mile is assumed here, which is 0.48 kWh/mile (see text, chapter 3) with the 80%, 75%, and 75% electrolyzer, bulk storage, and onboard storage losses, respectively, factored in.

It is important to reiterate that the above table represents preliminary data and studies, so the numbers cannot be taken at face value, except for a rough initial comparison. Further work must be done in order to verify and expand upon these results. For example, studies and analyses must look at upstream effects as well as waste or decommissioning costs, so that the total picture can be viewed. More importantly, studies must be done uniformly and consistently within and across all the fuels so that the results will have validity and credibility. To this end, acceptable and agreed-upon methods and practices must be established and followed. Still, it is quite likely that the relative differences between the fuels will not change by large amounts because of fundamental differences in the various fuels and technologies in terms of their "ability to pollute." To have reliable estimates for the various options' external costs, however, additional research must be done.

CHAPTER IX

Discussion and Conclusion

It is clear from the studies just reviewed that determining the external costs of transportation fuels is a tremendous task that is not yet complete. Not only were some of the environmental effects and impacts of automobile fuels not estimated, because of insufficient data or studies, but certain parts of the fuel cycle have been left out--usually the upstream environmental costs. Also, uncertainty remains in many of the other estimates calculated. While the figures derived are necessarily rough estimates ("starting point" values), they are often inevitably low estimates, where conventional fuels are still favored over new and/or environmentally friendlier fuels and technologies. Obviously, a great deal more work remains to be done in the estimation of external costs for light-duty vehicle fuels and technologies. Even then, it is likely that external cost estimates may never be completely accurate, as large uncertainties may still remain in some of the more elusive damage estimates. This, however, should not be a reason to reject the process of estimating externalities, as industries have coped with inherent uncertainties in quantifying other resource costs. For example, the electric utility industry's estimates of future load growth, construction costs, and fuel costs are laden with uncertainty (Buchanan 1990; Pace University 1991).

Furthermore, some of the latest and most pressing concerns of public utility commissions and the electric utility industry include the role of environmental and other externalities in industry planning, in spite of the fact that the valuation of environmental externalities is a discipline that is still in its infancy. Currently, 28 states and the District of Columbia require formal consideration of environmental externalities in utility planning and/or bidding processes or are considering doing so (Palmer and Dowlatabadi 1991). According to Pace University, seven states are seeking to actually quantify externalities for use in planning and bidding processes. Moreover, Burtraw and Krupnick (1992) of Resources for the Future argue that the methodology of external cost analysis brought forth by economists is "theoretically rigorous and allows environmental concerns to be treated in a comprehensive and consistent manner," and that in the last few years, economics has made tremendous advances in the valuation of external costs. Krupnick (1993) continues that a new external cost study currently being completed in cooperation with the DOE, Oak Ridge National Lab, and Resources for the Future will further improve upon the "commendable" Pace University study by developing a single comparable analytical methodology and by providing the best range of estimates of damage costs for six different full fuel cycles for the generation of electricity.[17] This new study will help meet the rapidly growing demand for reliable external cost figures and analyses for the electric utility industry.

Given the emphasis and importance of estimating external costs in the electric utility industry, it seems that significance will also be placed on the estimation and valuation of the external costs of transportation energy use. Moreover, the transportation sector will be able to benefit from the work being done on the estimation and valuation of externalities in the electric utility industry, perhaps speeding up the utilization and incorporation of externalities in personal transportation planning. Indeed, new legislation requires that the California Energy Commission estimate transportation fuel use externalities in order to identify a "least economic and environmental cost" transportation system for the state of California. Senate Bill 1214, which took effect on January 1, 1992, states that "...it is the policy of this state to fully evaluate the economic and environmental costs of petroleum use, and the economic and environmental costs of other transportation fuels, including the costs and values of environmental externalities, and to establish a state transportation energy policy that results in the least environmental and economic cost to the state" (California Energy Commission 1994).

The bill requires the commission to, among other tasks, assign economic values to a wide variety of impacts that result from transportation fuel use, including air pollution, water pollution, global warming, congestion impacts, energy security effects, and effects of price changes and supply disruptions on the economy and public welfare (CEC 1994). The alternative fuels that are being evaluated are gasoline, compressed natural gas, electricity, and methanol. In their two-year progress report, the commission recommends that the external costs associated with the use of a particular fuel be priced when the fuel is bought, and that social cost pricing strategies be considered because they appear to be "more economically efficient and powerful than alternatives such as standards or other

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[17]As of November 1995, 4 out of the 7 volumes are in the hands of the publisher (Utility Data Institute) and the rest of the set is expected to be available by the first quarter of 1996.

direct interventions." Furthermore, an organization that conducts in-depth, high quality public-issue polling found that two-thirds of the public believe that we can get the energy we need in such a way that it improves the environment, and that, surprisingly, the people agree to substantial increases in user fees and pollution charges (Kay 1992), which is not something that should be glossed over. Therefore, it seems that the estimation and incorporation of external costs for various alternative fuels for transportation will be an important task for future transportation decisions and planning, and this is already being acknowledged by legislation as well as an informed general public.

Ultimately, in order for decision makers and society to be able to choose auto fuels and technologies that have the least social cost, the external costs of their extraction, production, use, and waste disposal must be accounted for and incorporated in their prices. Currently, these external costs are ignored. From the conclusion presented in the external cost estimation section of this work, it is obvious that external costs of petroleum are significant. Moreover, decisions are currently made which lead to investment in fuels and technologies which impose substantial human health and environmental impacts on society. This doesn't mean that alternative solutions are readily available, or that their external costs are significantly lower. On the contrary, from the technology assessment presented in this work, alternative fuels and technologies require significant development work, and even then there are no guarantees that they will be economically competitive, even if social costs are considered. However, including external costs in the prices of alternative fuels will "level the playing field" and send the right signals to the market. Not only will conventional fuels be consumed more efficiently, but more importantly, society will be able to make more informed investment decisions in its choice of technologies, and research and development will be stimulated for fuels and technologies with the lowest social cost.

Market incentives, regulations, the quality of research and education, and social values and preferences all determine the direction that technology will develop and in which type of technology society will invest. Heaton, Repetto, and Sobin (1991) claim that perhaps the most fundamental impediment to the development of technological advance that is environmentally preferable and friendlier than what is currently available is the externality problem. They argue that "this pervasive market failure overshadows all other obstacles in energy, agriculture, and manufacturing." The internalization of external costs would change the relative rankings of various fuels and technological options, boosting the position of those that are favored for their environmental advantages. In this way, more effective planning for future transportation alternatives can be made possible. Moreover, it is this planning and forward-thinking that can save society a great deal in terms of environmental and economic costs, as well as time.

This work reviewed, summarized, and synthesized the current state of the technology for four alternative transportation fuels and the current studies that attempted to identify the external costs related to these alternatives. It is plain and clear that the development of environmentally-friendlier transportation fuels and technologies and the estimation of their external costs are areas of utmost importance for earth and society, so that society can plan for and have available options that have the greatest benefits and the lowest total costs, for the benefit of current and as well as future generations.

GLOSSARY

Contingent valuation method. A technique for measuring the benefits or costs associated with a resource or resource action; the technique relies on establishing hypothetical markets and querying respondents as to the value they place on the resource.

Control cost. The cost of avoiding or reducing an environmental effect at the source, usually applied to emissions; e.g., the cost of scrubbers to reduce SO_X emissions.

Discount rate. The interest rate used to convert future values to present values; a measure of the preference for receiving a benefit now rather than in the future.

Economic damage. The value of lost income or lost net economic product resulting from some activity, expressed in dollars.

Economic efficiency. Either 1) producing the maximum amount of some product at a given cost; or, 2) producing a given amount of some product at the lowest cost. Generally, economic efficiency means maximizing total net benefits or minimizing total net costs.

Energy efficiency. The ratio of the useful energy delivered by a dynamic system to the energy supplied to it.

Environmental benefit. Any change in an environmental good or service that increases net benefits to society, either by increasing quantity of the good or service or quality of the good or service.

Environmental cost. Any change in an environmental good or service that decreases net benefits to society, either by decreasing quantity of the good or service or quality of the good or service.

Environmental effect. Any change in an environmental good or service or natural resource as a result of the construction, operation, or decommissioning of an energy resource.

Externality. A residual or side effect of an economic activity in which a benefit or cost is conferred upon a party who is not a party to the original transaction either as a producer, consumer, or agent; e.g., air pollution from a coal-fired power plant.

Hedonic pricing. A technique for measuring the implicit price of resource attributes or characteristics associated with an environmental good; the price of the non-market good is given as a function of the quantities of various characteristics such that the coefficients on those characteristics represent implicit prices.

Revealed preference. The derivation of an economic value by observing behavior from which preferences are inferred; e.g., deriving recreational site values by travel costs which reveal how much people are willing to pay to recreate at a site.

Risk. The set of all possible responses, and their associated probabilities, to an environmental intrusion.

Social cost. The full cost of an energy resource including both internalized costs such as labor and fuel as well as external costs such as environmental costs; a perspective from which all costs borne by society as a whole are accounted for.

Uncertainty. The inaccuracy inherent in an estimate because of errors in measurement or in statistical specification of relationships.

Upstream costs. Costs occurring prior to plant construction or operation; typically refers to costs during materials or fuel extraction, fabrication, or transport; as distinguished from "downstream" costs.

Valuation. The monetization of changes in environmental goods and services.

LIST OF ACRONYMS

AFC	Alkaline fuel cell
AGA	American Gas Association
BTU	British thermal unit
CARB	California Air Resources Board
CFCs	Chloro-fluoro carbons
CNG	Compressed natural gas
DM	Deutsche Mark
DOE	(U.S.) Department of Energy
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EV	Electric vehicle
FCV	Fuel cell vehicle
FHWA	Federal Highway Administration
GRI	Gas Research Institute
ICE	Internal combustion engine
IEA	International Energy Agency
LEV	Low-emission vehicle
MW	Megawatt

NGV	Natural gas vehicle
NRC	Nuclear Regulatory Commission
OECD	Organization for Economic Cooperation and Development
PAFC	Phosphoric acid fuel cell
PEM	Proton exchange membrane
PG&E	Pacific Gas and Electric (Company)
PM10	Particulate matter (under 10 microns)
psi	pounds per square inch
PV	Photovoltaic
ROG	Reactive organic gases
SCAQMD	South Coast Air Quality Management District
SOFC	Solid oxide fuel cell
SPR	Strategic Petroleum Reserve
TTI	Texas Transportation Institute
ULEV	Ultra-low emissions vehicle
VOCs	Volatile organic carbon (gases)
WRI	World Resources Institute
WSEO	Washington State Energy Office

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