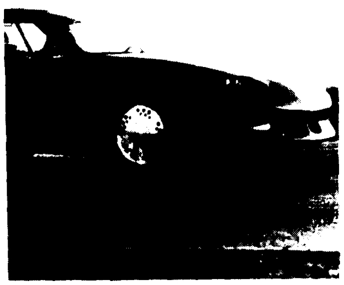
# Transport 4

Renewable fuels and advanced vehicle technologies have the potential to provide a large portion of our highway transportation energy needs. These fuels and technologies could substantially reduce oil imports, urban air pollution, and the emission of greenhouse gases, while providing jobs and income to rural areas. To realize this potential, however, will require a long and dedicated research and development (R&D) effort in order to achieve cost-effective, high-performance systems.

## WHAT HAS CHANGED IN TRANSPORT FUELS?

In the 1970s, the only renewable fuel considered seriously for transport in the United States was ethanol derived from corn.[1] Corn-to-ethanol production, however, is expensive. In addition, when all the energy inputs to grow com and convert it to ethanol are considered, there is—at best—a modest energy gain, with relative] y 1 ittle room for improvement compared with new technologies based on lignocellulose.

Advances in biotechnology are enabling researchers to convert cellulose to sugars that can be fermented to ethanol. These advances allow use of much cheaper feedstocks (e.g., wood, grass, and com stalks, rather than com grain) with relatively high yields. This has lowered the cost of biomass-derived ethanol[2] from



[1] In Brazil, ethanol from sugar cane was vigorously pursued.

[2] As used here, biomass-ethanol refers to ethanol produced from lignocellulose biomass feedstocks.

$4. 15/gal in 1980 to $1 .65/gal in 1993.[3] Advances in gasification and catalysis are also lowering the cost of producing methanol and hydrogen from biomass. As described in chapter 2, the production of the biomass itself has improved greatly.

Similarly, advances in energy conversion devices, particularly fuel cells, offer the prospect of high-efficiency propulsion systems that can use a variety of renewable fuels. For example, the amount of platinum catalyst necessary in the proton-exchange membrane (PEM) fuel cell has been greatly reduced. Ultimately, with other advances, this may make it possible to reduce the cost of such fuel cells with large-scale mass production to a level competitive on a vehicle life-cycle basis with internal combustion engines (ICES).

In addition, reductions in the cost and improvements in the performance of power electronics and electric motors are allowing the development of all-electric drivetrains as a substitute for today's mechanical gearbox and drivetrain. This may allow substantial increases in efficiency-both directly and indirectly through the use of regenerative braking (recovering the braking energy). Numerous other advances have occurred across many aspects of transport fuels and motive power technologies.

## | Potential Roles

The U.S. transportation system plays a central role in the economy.[4] Highway transportation, however, is dependent on internal combustion engine vehicles fueled almost exclusively by petroleum. This has given rise to a number of energy supply and environmental concerns. Despite substantial improvements in U.S. transportation energy efficiency in recent decades,[5] the United States still consumes more than one-third of the world's transport energy.[6] Transportation accounts for about one-quarter of total U.S. primary energy use and nearly two-thirds of oil use. About one-half of this oil is imported, costing the United States about $45 billion per year. Domestic oil production has declined since 1970 and is expected to continue declining while demand is expected to increase. With current policies, U.S. imports of oil are likely to increase dramatically over the next several decades (see chapter 1).

The U.S. dependence on oil not only makes the economy vulnerable to the supply and price vola-

~ 1992 $/gal. S.R. Venkateswaran, Energetics, Inc., and John Brogan, U.S. Department of Energy, personal communication, May 12, 1994. This includes approximately 35¢/gal for transport and delivery to the end user. Production costs above are approximately $3.80/gal and $ 1.30/gal, respectively. This does not include road transport fuel taxes.

4 The availability of reliable and efficient transportation systems has historically been an important determinant of economic growth. During the past 20 years, the demand for transportation goods and services in the United States has generally matched overall economic expansion and currently accounts for about one-sixth of the gross domestic product. See S.C. Davis and S.G. String, *Transportation Energy Data Book: Edi-[ion 12*, ORNL-6743 (Oak Ridge, TN: Oak Ridge National Laboratory, 1992), table 2-19.

5 Aggregate travel energy intensity (energy use per passenger-mile) in the United States has declined about 15 percent since 1973. This drop was principally due to the introduction of automobile fuel economy standards and higher oil prices. See L. Schipper, "Energy Efficiency and Human Activity: Lessons from the Past, Importance for the Future," paper presented at the Annual World Bank Conference on Development Economics, Washington, DC, May 3-4, 1993.

6 U.S. Congress, Office of Technology Assessment, *Changing by Degrees: Steps To Reduce Greenhouse Gases, OTA-O-482* Washington, DC: U.S. Government Printing Office, February 1991), p. 150.

tility of the world oil market, but also exacerbates local and global environmental problems. Motor vehicles currently account for 30 to 65 percent of all urban air pollution in the United States and up to 30 percent of carbon dioxide ($CO_2$) emissions.[7] Urban air pollution problems have motivated the development of a substantial body of federal and state regulations. Although urban air emissions from highway vehicles are expected to drop significantly[8] in this decade through improvements in engines, fuel systems, exhaust controls, and fuel characteristics, after the year 2000, carbon monoxide (CO) emissions are projected to begin growing due to increases in the number of vehicles on the road and total vehicle-miles traveled.[9]

In addressing the environmental and energy supply problems posed by our current transportation system, a number of approaches are possible. Creating incentives for reducing vehicle-miles traveled and promoting greater reliance on mass transit have been central components of recent federal legislation.[10] For the foreseeable future, however, the strong preference of American citizens for personal transport is unlikely to change. Thus, strategies that revolve around fuels produced from domestic resources, whose production and use involve minimal emissions of greenhouse gases (mainly $CO_2$) and criteria air pollutants (CO, sulfur oxides, nitrogen oxides, hydrocarbons, and particulates), are likely to become increasingly important. Renewable energy resources and technologies could help meet these objectives over the long term and could make unnecessary much of the regulatory overhead now in place for conventional fossil fuels and engine systems emissions. Indeed, efficiency improvements may not be sufficient to achieve long-run, deep cuts in $CO_2$ emissions unless there is a switch to renewable transport fuels.

Ethanol and methanol derived from biomass; diesel oil substitutes derived from oil-producing plants; electricity generated from renewables (chapter 5); and possibly, in the much longer term, hydrogen produced directly from biomass or electrolyzed from water by renewable-generated electricity are the principal renewable energy-based fuels that might substitute for today's petroleum-based liquids. If transportation fuels were derived from renewable sources such as solar, wind, or biomass energy, emissions of $CO_2$ would be largely eliminated (see table 4-1). Renewable fuels could also be used in zero- or near-zero-emission vehicles.[11]

[7]About 45 to 50 urban areas still violate the ozone quality standard, with emissions from highway vehicles—primarily automobiles and light trucks—contributing 40 to 50 percent of the volatile organic compounds (VOCs) and one-third of the nitrogen oxides that are the precursors of ozone. Evaporative emissions—as opposed to tailpipe emissions—may be responsible for more than 50 percent of automobile hydrocarbon emissions. Motor vehicles are estimated to be responsible for about 65 percent of carbon monoxide (CO) emissions. U.S. Environmental Protection Agency, *National Air Pollutant Emission Trends*, 1990-1992, No. EPA-454/R-93-03 (Washington, DC: October 1993); National Research Council, *Rethinking the Ozone Problem in Urban and Regional Air Pollution* (Washington, DC: National Academy Press, 1992); and J.G. Calvert et al., "Achieving Acceptable Air Quality: Some Reflections on Controlling Vehicle Emissions," *Science*, vol. 261, July 2, 1993, pp. 37-45.

[8]By the year 2000, compliance with the Clean Air Act Amendments of 1990 is expected to reduce CO emissions by 27 percent, nitrogen oxides by 19 percent, and volatile organic chemicals by 30 percent. See U.S. Environmental Protection Agency, op. cit., footnote 7.

[9]See U.S. Congress, Office of Technology Assessment, *Improving Automobile Fuel Economy: New Standards, New Approaches*, OTA-E-504 (Washington, DC: U.S. Government Printing Office, October 1991).

[10]The Clean Air Act Amendments of 1990 require the use of "transportation demand management"—especially during peak travel times—as a tool in reducing urban air pollution. The Intermodal Surface Transportation Efficiency Act of 1991 allows states to shift highway funds to transit, promotes new high-speed ground transportation systems, and generally establishes energy efficiency as a major goal of new transportation investment.

[11]Some alternative fuels such as methanol and hydrogen can be derived from both renewable (biomass) and nonrenewable sources (natural gas or coal). Although fuel-cycle emissions of $CO_2$ can be dramatically lowered by using renewable energy sources, vehicle tailpipe emissions of criteria air pollutants will be essentially the same for both renewable and nonrenewable derived fuels.

**TABLE 4-1: Projected $CO_2$-Equivalent Emissions of Greenhouse Gases, Circa 2000[a]**

| Feedstock/fuel | Fuel-cycle $CO_2$-equivalent emissions (grams/km)[b] | Change in $CO_2$-equivalent emissions (percent) |
|---|---|---|
| *internal combustion engine vehicles (ICEVs)* | | |
| Baseline Petroleum/reformulated gasoline[c] | 290 | 0 |
| Coal/methanol | 460 | ~ 58 |
| Coal/compressed $H_2$ | 440 | +52 |
| Corn/ethanol (E85)[d] | 210 to 320 | -27 to ~ 11 |
| Corn/dedicated ethanol (EI 00) | 210 to 320 | -27 to +11 |
| Natural gas/dedicated methanol (MI 00) | 270 | -6 |
| Natural gas/compressed $H_2$[e] | 220 | -25 |
| Natural gas/dedicated CNG[f] | 220 | -26 |
| Biomass/compressed $H_2$[g] | 70 | -75 |
| Solar/compressed $H_2$[h] | 50 | -82 |
| Biomass/methanol | 50 | -83 |
| Biomass/ethanol (E85) | 35 | -88 |
| Biomass/dedicated ethanol (EIOO)[i] | 0 to 30 | -90 to 100 |

[a]The estimates shown here are meant to illustrate the potential reductions in greenhouse gas emissions that are possible with a shift to renewable fuels; there is considerable uncertainty in some of the values listed.

[b]This is the sum of emissions of $CO_2$, $CH_4$, $N_2O$, CO, $NO_2$, and NMOCs from the entire fuel production and use cycle (excluding the manufacture of vehicles and equipment), per kilometer of travel, relative to the total g/km emissions for a year-2000 light-duty vehicle running on reformulated gasoline. All vehicles specified have the same total energy consumption. Emissions of gases other than $CO_2$ have been converted to an "equivalent" amount of $CO_2$ by multiplying mass emissions of each gas by the following "global warming potentials": $CH_4$, 21; $N_2O$, 270; CO, 2; $NO_2$, 4; NMOCs, 5. The resultant $CO_2$ equivalents of these gases have been added to actual $CO_2$ emissions, to produce an aggregate measure of greenhouse gas emissions. The results shown are from unpublished runs of an updated version of the greenhouse gas emissions model documented in M.S. DeLuchi, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, Report No. ANL/ESD/TM-2 (Argonne, IL: Argonne National Laboratory, Center for Transportation Research, November 1991).

[c]Projected greenhouse gas emissions for a year-2000 light-duty vehicle (26 mpg) operating on reformulated gasoline.

[d]Assumes use of 85-percent ethanol mixed with 15-percent gasoline in a "flexible-fuel" vehicle that can burn any mixture of alcohol and gasoline. It also assumes that the E85 flexible-fuel vehicle is 5 percent more efficient than the comparable dedicated gasoline/ICEV. The dedicated ethanol/ICEV (E100) is assumed to be 12 percent more efficient than the gasoline/ICEV because it can be optimized to run on ethanol, whereas the flexible-fuel vehicle cannot.

[e]Hydrogen is made at the refueling site from natural gas delivered by pipeline and then compressed to 8,400 psi for delivery to vehicles. The compressor uses electricity generated from the projected national mix of power sources in the United States in the year 2000.

[f]Natural gas is compressed to 3,000 psi for delivery to vehicles with high-pressure tanks.

[g]Hydrogen is made in centralized biomass gasification plants, then compressed for pipeline transport using electricity generated at the biomass plant. At the station, hydrogen is compressed to 8,400 psi for delivery to vehicles by a compressor using the projected year-2000 U.S. mix of power sources.

[h]Hydrogen is produced from water using solar power, delivered by pipeline to the service station, and then compressed to 8,400 psi for delivery to high-pressure tanks onboard vehicles. The hydrogen compressor at the refueling station runs off electricity generated from the projected national mix of power sources in the United States in the year 2000.

[i]Assumes advanced biomass-to-ethanol conversion technology and electricity cogeneration from corn residue.

TABLE 4-1 (cont'd): Projected $CO_2$-Equivalent Emissions of Greenhouse Gases, Circa 2000[a]

| Feedstock/fuel | Fuel-cycle $CO_2$-equivalent emissions (grams/km)[b] | Change in $CO_2$-equivalent emissions (percent) |
|---|---|---|
| *Battery-powered electric vehicles (BPEVs)* | | |
| Average U.S. power generating mix[j] | 250 | -14 |
| Solar power[k] | 0 | -90 to 100 |
| *Fuel cell electric vehicles (FCEVs)* | | |
| Coal/methanol | 210 | -27 |
| Coal/compressed $H_2$ | 180 | -37 |
| Natural gas/methanol | 120 | -58 |
| Natural gas/compressed $H_2$ | 90 | -69 |
| Biomass/compressed $H_2$ | 30 | -90 |
| Solar/compressed $H_2$ | 20 | -93 |
| Biomass/methanol | 17 | -94 |
| All solar/compressed $H_2$[l] | 0 | -90 to 100 |

[j]BPEVs are recharged at night using the extra electricity generated specifically to meet the BPEV demand.

[k]This BPEV is recharged from 100 percent solar power.

[l]The hydrogen compressor at the station runs on solar power.

KEY: CNG = compressed natural gas; $CH_4$ = methane; $H_2$ = hydrogen; mpg = miles per gallon; NMOC = nonmethane organic compounds; $N_2O$ = nitrous oxide; $NO_2$ = nitric oxide; psi = pounds per square inch.

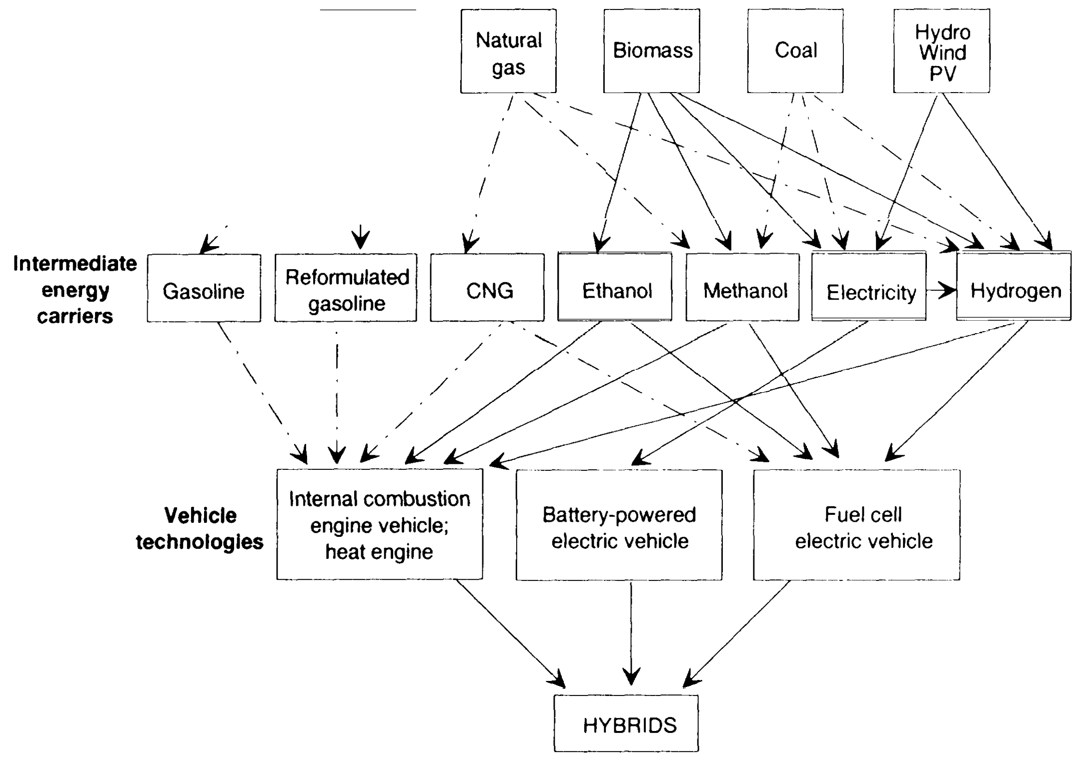
SOURCE: The estimates presented here are drawn from Joan M. Odgen et al., "A Technical and Economic Assessment of Renewable Transportation Fuels and Technologies," report prepared for the Office of Technology Assessment, May 1994.

Biomass-derived fuels such as ethanol, methanol, or hydrogen could satisfy a significant portion of transportation energy needs if used in conjunction with high-efficiency vehicle technologies such as hybrid electric vehicles or fuel cell-powered vehicles. Some estimates for potential bioenergy production range up to perhaps 25 EJ (24 quads) by 2030.[12] Current transportation energy requirements are about 24 EJ (23 quads) annually and are projected to increaseto31 EJ (30 quads) by 2010.[13] Thus, unless coupled with very aggressive efforts to improve vehicle fuel efficiency, biomass-derived fuels will probably not be sufficient to completely displace imported oil used for transportation. Wind and especially solar resources are potentially much larger than biomass. Although wind- or solar-derived hydrogen and electricity would not be resource constrained, their higher costs will still justify attention to raising vehicle efficiency. Whether or not the potential of renewable resources can be realized, however, remains uncertain and depends on their cost and performance compared with other fuels and technologies. The larger context of transport infrastructure development and accounting for the

[12]See chapter 2. This does not include conversion losses for biomass to liquid or gaseous fuels.

[13]U.S. Department of Energy, Energy Information Administration, *Annual Energy Outlook, 1994*, DOE/EIA-0383(94) (Washington, DC' January 1994).

FIGURE 4-1: Alternatives for Production and Use of Transportation Fuels




NOTE Renewable energy pathways are shown as solid lines

SOURCE Robert Williams and Henry Kelly, "Fuel Cells and the Future of the U S Automobile," n d

social costs of fossil fuel use and transport are also very important.[14]

## | Principal Themes

In this chapter, a variety of alternative technology pathways are outlined that would utilize renewable fuels and advanced propulsion systems. Their relative economic, environmental, and technological performance is analyzed vis-a-vis conventional fossil-fueled systems; key research, development, and demonstration (RD&D) and commercilization issues that may impede market introduction are examined; and various policy measures that could bring these renewable technology pathways to fruition are explored.

## RENEWABLE ENERGY PATHS FOR TRANSPORT

There are many possible options for automotive transportation. Some major options now under consideration are illustrated in figure 4-1, where various combinations of primary energy sources, intermediate energy carriers, and vehicle technologies are shown. Each fuel-propulsion system

[14]For a detailed discussion of the social costs of transportation, see U.S. Congress, Office of Technology Assessment, *Saving Energy in U.S. Transportation*, OTA-ETI-589 (Washington, DC: U.S. Government Printing Office, July 1994).

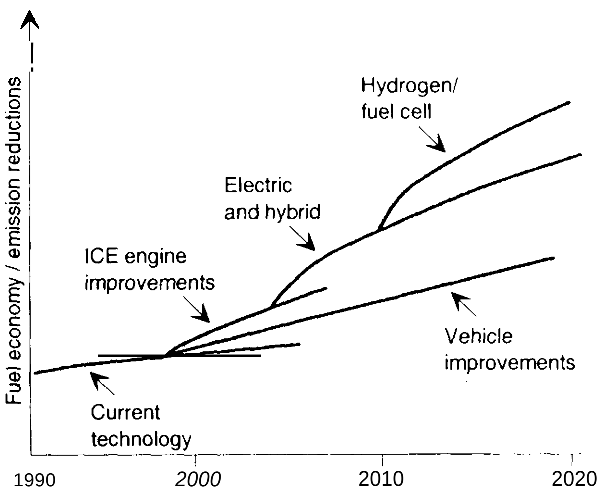
combination offers a different set of energy requirements, emission levels, and performance characteristics, as well as a different set of R&D challenges and commercial hurdles. Some technologies are relatively mature, whereas others are only now being explored. There is great uncertainty as to which of these fuel and vehicle technologies will prove most desirable; the many possible options, however, increases the likelihood that one or more will be successful.

The development and maturation of one technology can in some cases pave the way for more efficient solutions later on. For example, the use of methanol or ethanol in internal combustion engine vehicles (I CEVS) could lead to the creation of a bioenergy crop infrastructure that might later be shifted to bi s), Similarly, the creation of a natural gas distribution network for ICEVs—if properly designed and appropriate materials were used—might ultimately lay the groundwork for a hydrogen fuel infrastructure that could be used in advanced propulsion systems. [15] Thus, different fuel and vehicle technology alternatives are not necessarily mutually exclusive options but in some circumstances can serve as complementary strategies over the long term.

A variety of evolutionary paths can be outlined that lead from current technologies toward the use of renewable fuels in low-emission vehicles. One possible scenario is depicted in figure 4-2. Over the course of the next decade, for example, ICEVs operating on compressed natural gas (CNG), methanol made from natural gas, or ethanol made from corn might be introduced on a wide scale. [16] The use of natural gas or alcohols in conventional vehicles offers a relatively low-risk strategy for reducing petroleum dependence in the short term.

Depending on the particular fuel and vehicle technology, reductions in emissions of criteria pollutants could be modest (ethanol and metha-

**FIGURE 4-2: Transportation Technology Pathway**




NOTE: The evolution toward low-emission, high-efficiency vehicle systems could take many different directions. Pure electric vehicles or hybrid electric vehicles could emerge as important technologies. Hybrid propulsion systems combine two power sources, potential power sources include batteries, flywheels, internal combustion engines, gas turbines, fuel cells, and diesel engines. All vehicle technologies will benefit from the introduction of light-weight materials, reductions in drag and rolling resistance, and improvements in mechanical or electric drive losses. Both conventional and emerging vehicle technologies can take advantage of energy carriers such as methanol, ethanol, hydrogen, and electricity that can be derived from renewable sources.

SOURCE U S Department of Energy Off Ice of Transportation Technologies

[15] Hydrogen can be produced by steam reforming of natural gas. If a network of natural gas service stations were developed, a decentralized hydrogen infrastructure might be created fairly quickly. Since stationary fuel cell applications are likel y to be commercially available well before transportation applications, it may be possible to tap into natural gas steam reformers at these stationary sites for refueling of hydrogen ICEVs or FCVs. Paul Miller, W. Alton Jones Foundation, personal communication, Apr. 19, 1994.

16 Hydrogen (from natural gas or biomass) and ethanol ( from cellulosic biomass) are unlikely to be widely available in the next 10 years. Hydrogen faces infrastructure limitations, and ethanol derived from cellulose is still in the development and early pilot production phase. Com-based ethanol is already in use but is unlikely to be more than a transition fuel since other sources are more promising economically.

no]) to significant (CNG) to dramatic (hydro-gcn ).[17] Reductions in $CO_2$ would similarly vary widely depending on the fuel and vehicle technology. over the long term. more substantial reductions in greenhouse gas emissions could be accomplished through the production of methanol, ethanol, or hydrogen fuels from renewable energy sources such as cellulosic biomass (see table 4-l ).

If petroleum use is to be reduced significantly, propulsion systems with relatively high efficiencies arc necessary. Such efficiency requirements might be met in the mid-term by hybrid vehicles that, for example. combine a small ICE with a battery and an electric motor(s) driving the wheels. Hybrid systems may be able to provide many of the energy efficiency and emissions bencilts of pure battery-powered electric vehicles (BPEVs), while offering greater flexibility with respect to range and performance. An ICE-based hybrid could run on a variety of fuels such as hydrogen, ethanol, methanol. or reformulated gasoline. Research on hybrid systems could also speed the development of electric drivetrain technologies and advancd power control systems. Much RD&D remains, however, to determine hybrid vehicle cost and performance.

When cost-competitive, the ICE portion of the hybrid could be replaced with a fuel cell, gas turbine, or advanced diesel engine. The ICE hybrid could thus allow a significant decoupling of the various components of the vehicle system, permitting development of the fuel infrastructure that powers the ICE to be largely separated from development of the electric drivetrain. This could facil i-tate the introduction of fuel cell electric vehicles over the long term (e.g., a methanol or hydrogen infrastructure could be developed first for ICE hybrids and then used to supply energy for fuel cell-bascd hybrids).

The introduction of fuel cell vehicles operating on methanol or hydrogen from natural gas would substantially reduce both criteria pollutant and $CO_2$ emissions (because of the higher efficiency of FCVS).[9] Fuel cell vehicles running on hydrogen produced from biomass or renewably generated electricity, or alcohol (methanol or ethanol) produced from biomass, are potentially the cleanest and highest performance systems. A decade or more of intensive RD&D remains to bc done, however, before their technological and economic feasibility can be fully determined.

Many key fuel cell technologies arc still in the developmental phase. Although some advances have been made in the area of PEM fuel ccl] performance, much progress is required before a complete fuel cell system can be commercially packaged for an automobile. The reliability y of the essential components of a fuel cell system has not yet been demonstrated in an automotive environment or over a typical automotive duty cycle. Although fuel ccl] costs will likely drop as economics of scale are achieved in manufactur-

I 7 Although alternative fuels such as methanol, ethanol, and natural gas are "inherently" less ozone-forming and less carcinogenic than gasol inc. new regulatory requirements for gasoline could very likely diminish the environmental advantage of alternat i ve fuels. See D. E. ~JU-Ace. "Alternative Fuels for Automobile\: Are They Cleaner Than Gasoline'?" Congressional Research Service Repro 92-235 S, Feb. 27, 1992; also see Alan J. Krupnick et al., Resources for the Future, "The Cost-Effectiveness and Energy Security Benefits of Methanol Vehicles." Discus-i ion Paper QE90- 25, September 1990; and J. Odgen et al., "A Technical and Economic Assessment of Renewable Transportation Fuel\ and Technologies\, " report prepared for the Office of Technology Assessment, May 1994.

18 The ICE would be used t. generate electricity (o power an electric motor drivetrain, and the battery would provide "peak power" to meet acceleration or hill-climbing demands. Unlike conventional ICEVs, in which the powerplant (the engine ) drives the wheels directly, a hybrid or pure electric vehicle uses the powerplant (e.g., heat engine. fuel cell, or batter]) to drive electric motors that drive the wheels.

19 Fuel cells are electrochemical devices that convert the chemical energy in a fuel (hydrogen is preferred) and oxidant (usually oxygen in ai r ) directly Into electrical energy. Unlike batteries, the reactants are supplied continuously from an external source (e. g., a hydrogen storage tank plus air). The main exhaust product of a fuel cell is water. Over a typical urban driving cycle, fuel cell -propelled vehicles could potentially have two to three times the efficiency of ICEVs.

ing, the reductions necessary to make FCVs competitive with other vehicle options will require intensive engineering and manufacturing development in coming years.[20]

BPEVs have the potential to directly displace significant amounts of imported oil because just 4 percent of U.S. electricity is generated from oil, and most of this is for peaking power, yet virtually every trip they make would otherwise have been made by a gasoline or diesel-fueled vehicle. BPEVs could offer significant energy efficiency and environmental benefits. BPEV tailpipe emissions would be zero, while the magnitude of $CO_2$ and other emissions would depend on the marginal electric power generation mix of a particular region.[21] Emissions would be lower for advanced natural gas powerplants than for coal, due to their higher efficiency and the inherent cleanliness and high-energy content of natural gas. Further reductions in greenhouse gas emissions could be achieved through greater use of renewable energy sources or nuclear power by electric utilities.

At present, however, no existing battery technology would allow a pure BPEV to be fully competitive with a conventional ICEV.[22] In the near term, BPEVs are most likely to be used as secondary vehicles for commuting and short trips. In addition to vehicle performance (determined primarily by battery technology), the upfront vehicle costs and the life-cycle operating costs of BPEVs will determine the viability of this technology option. The economic, technical, and environmental characteristics of the more plausible fuel-vehicle combinations arc examined in detail in the followin: sections.

## A RENEWABLE FUEL MENU[23]

A variety of transportation fuels can be produced from renewable resources. The discussion here focuses on the four most promising energy ariers that could be used in conjunction with low'-cmission vehicles: methanol, ethanol, hydrogn ($H_2$). and electricity. Many of the comercilizaeion issues affecting alternative transport fuels have been addressed previously in the Office of Technology Assessment (OTA) report *Replacinq Gasoline .- Alternative fue1 for Light-Duty Vehicles* particularl the difficulties inherent in dcveloping a new fuel distribution infrastructure.[24] The principal technical and economic challenges facing renewable fuels are dcscribed below.

### |Methanol

Methanol is a liquid fuel that can be produced from natural gas, coal. or biomass. Onc major advantage of methanol is that it would requirc fewer changes in vehicle design than some other alternative fuels, Flexible-fuel vehicles. which can operate on methanol, ethanol, gasoline, or a mixture of these fuels, arc already being produced in limitcd numbers in the United States.[25] The use of such vehicles could case the transition from gasoline. Although methanol is frequently discussed as a re-

[20] A recent study by Allison-GM estimates that the initial purchase costs of a mass-produced FCV could be comparable to a conventional ICEV. Life-cycle operating costs may also be comparable. See Allison Gas Turbine Division, "Research and Development of Proton- Exchange Membrane (PEN!) Fuel Cell S? stem for Transportation Applications: Initial Conceptual Design Report," EDR 16194. report prepared for the U. S. Department of Energy, Office of Transportation Technologies, Nov. 30, 1993.

[21] The "marginal mix" is a measure of the power generation that must come online due to BPEV charging and is above and beyond the non- BPEV electricity demand.

[22] No existing battery technology possesses the necessary energy density (for range), power density (for acceleration performance), longevity, low cost, or quick recharge characteristics that would allow BPEVs to be comparable to conventional ICEVs.

[23] The discussion in this section draws heavily from Odgen et al., op. cit., footnote 17.

[24] U.S. Congress, Office of Technology Assessment, *Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles*, OTA-E-364 (Washington, DC: U.S. Government Printing Office, September 1990).

[25] Ibid., p. 25.

## BOX 4-1: Methanol Production from Biomass

Three basic thermochemical (high-temperature) processes are Involved in methanol production from biomass, The first step IS production of a "synthesis gas" via thermochemical gasifcation of biomass, using oxygen rather than air in order to eliminate dilution of the product gas with nitrogen (in air). Since oxygen plants have strong capital cost scale economies, most proposals for biomass-to-methanol facilities have Involved large plants (typically 1,500 metric tonnes/day input of dry biomass), Biomass gasiflers designed for methanol production are not available commercially. A number of pilot- and demonstration-scale units were built and operated in the late 1970s and early 1980s, but most of these efforts were halted when 011 prices fell, [1] Work on a fluidized-bed design has been revived, with the construction of a bagasse-fueled demonstration and now being planned.[2] More recently, indirectly heated gasifiers have been proposed,[3] These would produce a nitrogen-free gas without using oxygen and thus might be built economically at a smaller scale.

Second, the synthesis gas IS cleaned and its chemical composition is adjusted The specific equipment will vary depending on the gasifier used. Common to all systems is a "shift" reactor, which IS a commercially established technology, Other processing maybe required before the shift stage, however. For example, tars contained in the synthesis gas must be removed or cracked into simpler forms that WiIl not deposit on and/or damage the turbine.

Third, the gas IS compressed and passed through a pressurized catalytic reactor that converts carbon monoxide and hydrogen into methanol. A variety of commercial processes can be used.

This thermochemical process is Inherently more tolerant of diversity in feedstocks than biological processes (e g., enzymatic hydrolysis used in ethanol production),

[1] A A C M Beenackers and W P M van Swaaij, "The Biomass to Synthesis Gas Pilot Plant Programme of the CEC A First Evaluation of Results, " *Energy from Biomass, Third European Community Conference* (Essex, England Elsevier Applied Science, 1985), pp 120-45, and E D Larson et al , "Biomass Gasification for Gas Turbine Power Generation, " *Electricity Efficient End-Use and New Generation Technologies, and Their Planning Implications* (Lund, Sweden Lund University Press, 1989), pp 697-739

[2] R J Evans at al , Battelle Pacific Northwest Laboratory, "Development of Biomass Gasification To Produce Substitute Fuels, " PNL-6518, 1988

[3] C E Wyman et al , "Ethanol and Methanol from Cellulosic Biomass, " *Renewable Energy Sources for Fuels and Electricity,* T B Johansson et al (eds ) (Washington, DC Island Press, 1993), and E D Larson et al , Center for Energy and Environmental Studies, Princeton University, "ProductIon of Methanol and Hydrogen for Vehicles from Biomass, with Comparisons to Methanol and Hydrogen Product Ion from Natural Gas and Coal, " forthcoming

placement for gasoline, it can also be used to replace diesel.

Methanol is currently produced primarily from natural gas, but it can also be produced from coal and, through a similar process, from lignocellulosic biomass feedstocks.[2b] Biomass-to-methanol plants can convert 50 to 60 percent of the energy content of the input biomass into methanol, and some designs have been proposed with conversion efficiencies of more than 70 percent. Box 4-1 describes the basic processes.

Two possibilities are interesting, both involving feedstocks that are produced today. One option is the use of residues produced by the forest products industry, which today is the largest organized user of biomass energy in the United States.

[26] C.E. Wyman et al., "Ethanol and Methanol from Cellulosic Biomass," *Renewable Energy: Sources for Fuels and Electricity,* T.B. Johansson et al. (eds.) (Washington, DC: Island Press, 1993).

TABLE 4-2: Estimated Baseline Retail Fuel Prices (1991 dollars), Post-2000

| Transport fuel | Feedstock/electricity source | Feedstock/electricity cost | Delivered cost to consumer ($/GJ)[a] |
|---|---|---|---|
| Methanol | Biomass | $2.50/GJ | $13-15[b] |
| Methanol | Natural gas | $3/GJ | 11-13 |
| Methanol | Coal | $1.75/GJ | 13 |
| Ethanol | Biomass | $2.50/GJ | 10-15 |
| Ethanol | Corn | $1/bushel | 14-19 |
| Hydrogen | Biomass | $2.50/GJ | 14-16 |
| Hydrogen | Photovoltaic | 6-15 ¢/kWh | 25-60 |
| Hydrogen | Wind | 5-8 ¢/kWh | *30-40* |
| Hydrogen | Natural gas | $3/GJ | 11 |
| Hydrogen | Coal | $1.75/GJ | 14 |
| Hydrogen | Nuclear | 5-8 ¢/kWh | 26-33 |
| CNG | Natural gas | $3/GJ | 7-8 |
| Reformulated gasoline | Crude 011 | $26/barrel[c] | 9 |
| **Utility residential electricity rates for recharging battery-powered electric vehicles[d]** | | | |
| Offpeak power | | | 4-6 ¢/kWh |
| Conventional utility | | | 6-8 ¢/kWh |
| Renewable-intensive utility | | | 4-10 ¢/kWh |

[a] 1 gigajoule (GJ) 109 Joules = O 95 m II I ion BTUS 278 kilowatt-hours, 1 gallon of gasoline = O 13 GJ 1 gallon of methanol = O 065 GJ 1 gallon of ethanol -0087 GJ $1 gallon of gasoline = $7 67/GJ

[b] Methanol ethanol and hydrogen fuels can be burned in ICES with higher compression ratios and thus can operate more efficiently than gasol ne engines This should be taken into consideration when comparing alternate fuels with gasoline

[c] Based on Department of Energy projections for fossil energy prices (post-2000) in 1991 dollars See U S Department of Energy Energy I r? formation Administration *Annual Energy Outlook 1994, DOE-EIA-0383(94)* (Washington, DC U S Government Printing Off Ice, January 1994)

[d] Although the cost of electricity (4 to 6 ¢/kWh o,$11 to $17/GJ) is relatively **high** compared to gasoline ($9/GJ), the actual **Operating** electricity costs for BPEVS are likely 10 be substantially lower than for gasoline vehicles, due principally to the efficiency advantage of electric vehicles

SOURCES The estimates presented here are drawn principally from Joan M Odgen et al "A Technical and Economic Assessment of Renewable Transportation Fuels and Technologies," report prepared for the Off Ice of Technology Assessment, May 1994, and U S Department of Energy Biofuels Program 1994

Forest residues associated with annual wood harvests for the industry contain some 1.3 EJ.[27] A second feedstock stream is municipal solid waste (MSW). This source, amounting to about 1.8 EJ per year (after recycling), is especially attractive because of its negative cost (e.g., it costs money to dispose of it). The gasification technology needed for MS W is essential y the same as that required for biomass.

Since biomass-to-methanol plants are not yet commercially available, costs are uncertain (table 4-2 gives one estimate of baseline alternative fuel production costs for the post-2000 timeframe). From scattered cost data, it is estimated that methanol from biomass could be produced for about $14/GJ, equivalent to $1 .85/gal gasoline, with commercially ready technology in a plant with a capacity of about 10 million GJ/yr (about 500 mil-

[27] Anthony F. Turhollow and Steve M. Cohen, Oak Ridge National Laboratory, "Data and Sources: Biomass Supply," draft report, Jan. 28, 1994.

lion liters/year or 130 million gal/year). Methanol derived from natural gas costs about $1l/GJ ($1 .45/gal gasoline), while production of methanol from coal costs about $ 13/GJ ($1.70/gal gasoline). Compared with reformulated gasoline (even at $26/barrel for crude oil), methanol—regardless of the primary energy source—is marginally competitive at best. As discussed below, however, methanol can potentially be used at much higher efficiency than gasoline, e.g., in FCVs, offsetting its higher cost.

Capital represents the largest fraction of the total cost of methanol produced in small plants, whereas feedstock is the dominant cost in large plants. Thus, capital cost reductions will be most important in reducing methanol costs from small plants, while increases in biomass conversion efficiency will be most important on a large scale. As a liquid fuel, methanol would carry distribution and retailing costs that are approximately the same per unit volume as gasoline. The volumetric energy density of methanol is roughly half that of gasoline, however, resulting in a reduced range for methanol-fueled vehicles (for a given storage tank volume and engine type) and higher distribution and retailing costs on an energy-equivalent basis.

The use of pure methanol could reduce air pollution, particularly urban smog. As with other alternative fuels, methanol has a number of attributes that appear superior to gasoline.[28] In particular, methanol:

- *has lower volatility than gasoline, which should reduce evaporative emissions.*
- *has a lower photochemieal reactivity than gasoline.* As a consequence, emissions of unburned methanol, the primary constituent of methanol vehicle exhaust and fuel evaporative emissions, have less ozone-forming potential than an equal weight of organic emissions from gasoline-fueled vehicles.
- *has higher octane and wider flammability* ***lim*** *- its than gasoline.* This allows a methanol engine to be operated at higher (leaner) air-to-fuel ratios than similar gasoline engines, promoting higher fuel efficiency and lower CO and organic emissions.

In addition, if produced from biomass feedstocks grown on a renewable basis, methanol would provide a substantial $C0_2$ benefit over gasoline. However, any benefits are highly dependent on the feedstock. Methanol from coal, for example, would result in higher $CO_2$ gas emissions.[29] Methanol does have some environmental disadvantages, particularly greater emissions of formaldehyde, which could require special emission controls. The liquid fuel itself is toxic,[30] moderately corrosive, and highly flammable; thus, some modifications to the existing fuel distribution system are expected to be required.

It should also be noted that, under pressure from both state and federal regulation, gasoline is being improved to reduce its emissions and new emissions control technologies are nearing commercialization. These developments could effectively eliminate the exhaust emission advantages of alternative fuels such as methanol and ethanol. On the other hand, new formulations of gasoline must contain oxygenates such as ethanol or derivatives of either methanol (e.g., methyl tertiary-butyl ether, MTBE) or ethanol (e.g., ethyl tertiary -butyl ether, ETBE). The addition of oxygenates to gasoline can reduce CO formation but appears to offer little benefit in terms of reducing atmospheric ozone levels.

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[28] As an additive to gasoline, however, methanol provides little or no air quality advantages except for the reduction of carbon monoxide. There are significant evaporative emissions that can affect ozone formation when alcohol fuels are blended with gasol inc. See Calvert et al., op. cit., footnote 7.

[29] Office of Technology Assessment, op. cit., footnote 24, p. 71.

[30] Methanol, however, lacks the toxics (e.g., benzene) found in gasoline and thus can reduce levels of carcinogenic emissions.

In the longer term, a potentially important advantage of methanol fuels is their possible use in fuel cell vehicles (see below). Since methanol can be derived from a variet y of different sources and can be used in both conventional and advanced propulsion systems, it could play an important role in moving away from a fossil fuel-based transportation system.

## | Ethanol

Ethanol, like methanol, is a liquid fuel that can be used in internal combustion engines. It can be produced from biomass—about one-third of Brazil automobile fleet, for example, runs on straight ethanol produced from sugars The vehicle-related technical issues for ethanol are essentially the same as for methanol-it requires only minor modifications for use in gasoline engines, but more involved changes are required for use in diesel engines.

Generally, emissions from ethanol vehicles are expected to be similar to those from methanol vehicles, except that acetaldehyde, rather than formaldehyde, will be elevated. Ethanol, like methanol, is inherently less ozone-forming and less carcinogenic than gasoline.[s]~

As previously noted, new controls on gasoline are likely to reduce or even eliminate the exhaust emission advantages of ethanol and methanol. Ethanol can be used either as an additive to gasoline or directly. As an additive, its primary environmental benefit is a reduction of CO. However, gasoline-ethanol blends that contain low percentages of ethanol (e.g., 10 percent) increase the volatility of gasoline, thus increasing the mass evaporative emissions that can react with sunlight to form ozone. By using ETBE, an ethanol derivative, instead of ethanol itself, the volatility problem can be avoided.[33] This is also true when 100-percent ethanol (E1OO) is used. E85 (85 percent ethanol, 15 percent gasoline) has evaporative emissions comparable to gasoline.

The emissions of $C0_2$ from the full fuel cycle for ethanol vehicles vary greatly depending on the feedstock from which ethanol is produced. With corn, the emissions have been estimated to range from modestly lower to slightly higher than those of gasoline, due to the need for fossil fuel use in the production of the corn and ethanol.[34] On the other hand, if ethanol is made from cellulosic biomass, $C0_2$ emissions could be reduced dramatically (table 4-1 ).

The overall energy balance for corn-based ethanol is only modestly positive, at best. If the byproducts of ethanol production (e.g.. $C0_2$ and distilled grains for cattle feed) and the energy inputs required to grow corn (e.g., fertilizers, herbicides, and machinery fuel) are incorporated into an overall energy balance, the net energy gain of corn-based ethanol is estimated to range from -2 to +34 percent (i.e., there can be a fuel-cycle-wide net energy loss of 2 percent or a net energy gain up to 34 percent) compared with fossil[35] energy inputs.[36] This energy balance does not take account

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31 World Bank, "Alcohol Fuel\ from Sugar In Brazil," *The Urban Edge*, October 1990, p. 5.

32 Ethanol is however, somew hat more photochemically reactive than methanol and thus can give rise to slightly higher concentrations of ozone than methanol. Gushee, op. cit., footnote 17.

33 ETBE has a lower vapor pressure *than* MTBE, but because ethanol costs more than methanol as a feedstock, MTBE had been the ether of choice. How ever, on June 30, 1994. the Environmental Protection Agency promulgated a rule that, beginning in 1995, 15 percent of gasoline oxygenates must come from "renewable" sources, which in practice means ethanol or ETBE. In 1996, the renewable-based oxygenates would increase to 30 percent. This rule was overturned by a U.S. Court of Appeals on April 28, 1995.

34 Some estimates show that $C_{om}$-$d_{eri}v_e$d ethanol can slightly reduce overall $CO_2$ emissions. Further research IS needed to clarify this issue.

35 There may be some nuclear- and hydro-generated electricity inpUtS as well.

36 John Bailey, Institute for Local Self Reliance, personal communication, June 1, 1994.

NATIONAL RENEWABLE ENERGY LABORATORY

*At the National Renewable Energy Laboratory, a pilot-scale production plant converts cellulose to ethanol.* **Left:** *Biomass feedstock is washed and pretreated before conversion.* **Right:** *Four 9,000-liter fermentation tanks allow scale-up of promising conversion processes*

of the corn stover (field residue).[37] The stover contains more than enough energy to operate a corn-to-ethanol plant, so the net energy fraction might improve considerably if a portion of the stover were collected and used to replace external energy sources.

Another major issue with ethanol is the cost of production. It is heavily dependent on the cost of the feedstock (corn in the United States, sugar in Brazil) and the market value of the byproducts. Among potentially renewable fuels, ethanol (primarily from corn) is the only one that is produced commercially on a largc scale in the United States. It is used principally as a 10-percent blend with gasoline in Conventional ICEVs. About 3 billion liters of ethanol arc made annually in the United States, almost all from corn. Ethanol from corn is not cost-competitive with gasoline, so federal subsidies (currently about 54¢/gal) are necessary to support continued production.

### *Ethanol from Lignocelluiose*

The high cost of corn-based ethanol has motivated efforts to convert lower cost biomass, primarily woody and herbaceous materials. into ethanol. These feedstocks are less costly than corn because much larger quantities can be produced per land area and fewer agricultual chemical or other inputs are required. In addition, they do not directly compete with food crops.[38] They are, however, more difficult-and to date more costly-to convert into ethanol. Advances in biotechnology may change this outlook. Research by the National Re-

[37] G.O. Benson and R.B. Pearce, "Corn Perspective and Culture," *Corn: Chemistry and Technology, American Association of Cereal Chemists* (St. Paul, MN: 1987).

[38] Of course, they may compete with food crops indirectly in terms of land use, see chapter 2

newable Energy Laboratory (NREL) and others into cellulose-to-ethanol processes is promising and, if successful, could offer a cost-effective means of producing ethanol in very large quantities.[39]

Woody and herbaceous biomass, referred to generally as lignocellulosic material, consists of three chemically distinct components: cellulose (about 50 percent), hemicellulose (25 percent), and lignin (25 percent).[40] Most proposed processes involve separate processing-either acid or enzymatic hydrolysis-of these components. In the first step, pretreatment, the hemicellulose is broken down into its component sugars and separated out. The lignin is also removed. The cellulose is then converted into fermentable glucose through hydrolysis. After fermentation, the products are distilled to remove ethanol. Byproducts of the separation process, such as lignin, can be used as fuel.

### Acid Hydrolysis

A number of variants on the basic process of acid hydrolysis have been proposed, each typically involving use of a different acid and/or reactor configuration.[41] One system incorporates two stages of hydrolysis using dilute sulfuric acid. In the first step, the acid breaks the feedstock down into simple sugars. The acid also degrades some of the product sugars, however, so that they cannot be fermented, thus reducing overall yield. R&D has been aimed at improving the relatively low yields (55 to 75 percent of the cellulose) through the use of other acids.[42] Low-cost recovery and reuse of the acids are necessary to keep production costs down but have yet to be commercially proven.[43]

The estimated total cost of producing ethanol by different proposed acid hydrolysis processes is high ($15 to $20/GJ or $2.00 to $2.60/gal gasoline).[44] The potential for cost reduction is limited because the maximum overall efficiency of converting energy in the biomass feedstock by acid hydrolysis is only about 30 percent. The sale of chemical byproducts (e.g., furfural) improves economics, but the potential market is much smaller than production by a large-scale fuel ethanol industry.[45] Byproduct electricity could also offset ethanol costs, but the amounts of exportable electricity coproduced in process configurations to date have been relatively small. This situation might change if more advanced cogeneration technologies are considered (see chapter 5).

Unless world oil prices rise considerably (to $40/barrel or more), ethanol from acid hydrolysis appears to be an unpromising technology, particu -

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[39] One recent econometric study estimated that the agricultural sector could support the production of roughly 10 EJ (current national transportation energy consumption is about 22 EJ) of delivered ethanol from cellulosic biomass (not from, e.g., grain or sugarcane). Of course, this will also depend on export opportunities for agricultural commodities and other factors (see chapter 2). Randall A. Reese et al., "Herbaceous Biomass Feedstock Production: The Economic Potential and Impacts on U.S. Agriculture," *Energy Policy,* July 1993, pp. 726-734.

[40] Percentages vary for different species. Wood consists of about 50 percent cellulose and 25 percent hemicellulose. Grasses have roughly equal amounts of cellulose and hemicellulose (between 30 and 35 percent). J.D. Wright, "Ethanol from Lignocellulose: An *Overview,* "*Energy Progress, vol. 8, No. 2,* 1988, pp. 71-78; and Anthony Turhollow, Oak Ridge National Laboratory, personal communication, Apr. 22, 1994.

[41] Wyman et al., op. cit., footnote 26.

[42] See J.D. Wright et al., *Evaluation of Concentrated Halogen Acid Hydrolysis Processes for Alcohol Fuel Production,* SERI/TR-232-2386 (Golden, CO: Solar Energy Research Institute, 1985).

[43] Ibid.

[44] E.D. Larson et al. "Biomass-Gasifier Steam-Injected Gas Turbine Cogeneration for the Cane Sugar Industry," *Energy from Biomass and Wastes XIV,* D.L. Klass (cd. ) (Chicago, IL. Institute for Gas Technology, 1991),

[45] See P.W. Bergeron et al., "Dilute Acid Hydrolysis of Biomass for Ethanol Production, " *Energy from Biomass and Wastes XII* (Chicago, IL: Institute for Gas Technology, 1989), pp. 1277- 1296; and M.M. Bulls et al., "Conversion of Cellulosic Feedstocks (o Ethanol and Other Chemicals Using TVA's Dilute Sulfuric Acid Hydrolysis Process," *Energy from Biomass and Wastes XIV,* D.L. Klass (cd.) (Chicago, IL: Institute for Gas Technology, 1991).

larly in light of developments in enzymatic hydrolysis.

### *Enzymatic Hydrolysis*

Enzymatic hydrolysis of cellulose has been under development for about two decades. Advances that have been made in this technique specifically, and in biotechnology more generally, suggest that economically competitive commercial systems could be developed by early in the next century.

Biological enzymes typically break down only the cellulose and do not attack the product sugars. Thus, in principle, yields close to 100 percent can be achieved from cellulose. A feedstock pretreatment step is typically required since biomass is naturally resistant to enzyme attack. The most promising option appears to be a dilute acid, in which the hemicellulose is converted to xylose sugars that are separated out, leaving a porous material of cellulose and lignin that can be attacked more readily by enzymes.[%]

A number of bacteria and yeasts have been identified and tested as catalysts of cellulose hydrolysis. Three process configurations have received the most attention from researchers:

- In the separate hydrolysis and fermentation (SHF) of cellulose, three distinct operations are used to produce enzymes, hydrolyze cellulose, and ferment the glucose.
- A promising modification of the SHF process involves simultaneous saccharification and fermentation (SSF) in a single-reaction vessel, permitting higher product yield and improved economics.[47] Projected total biomass energy conversion efficiency to ethanol with improved xylose fermentation is about 64 percent.[48] The projected costs for ethanol produced by this method range from $10 to $15/GJ ($1 .30 to $2.00/gal gasoline) (roughly similar to the cost for biomass-derived methanol) delivered to the consumer.[49] Research lowered the cost of biomass-derived ethanol from $4. 15/gal in 1980 to $1.65/gal in 1993, including the cost of delivery.[50]
- Single-reactor direct microbial conversion (DMC) combines enzyme production, cellulose hydrolysis, and glucose fermentation in a single process. In limited efforts to date, however, DMC ethanol yields have been lower than those from the SHF or SSF processes, and a number of undesired byproducts have resulted.

A potential complication for ethanol production is that the enzymes currently used in the most promising conversion process---ezymatic hydrolysis—may require relatively homogeneous feedstocks to achieve projected performance.[51] Although researchers have been able to convert wastepaper and agricultural and forest product wastes into ethanol using enzymatic hydrolysis.[52] it may prove easier and less expensive to harvest and process a monoculture. From an ecological perspective, however, the ability to draw on biomass polycultures would be preferable in the longer term (chapter 2). If polyculture feedstocks are pursued, they may require the development of improved enzymes and processing technologies.

[46] J.D. Wright, "Ethanol from Biomass by Enzymatic Hydrolysis," *Chemical Engineering Progress,* August 1988, pp. 62-74.

[47] J.D. Wright et al., *Simultaneous Saccharification and Fermentation of Lignocellulose: Process Evaluation* (Golden, CO: Solar Energy Research Institute, 1988).

[48] Wyman et al., op. cit., footnote 26.

[49] Ogden et al., op. cit., footnote 17.

[50] 1992 $/gallon. Venkateswaran and Brogan, op. cit., footnote 3.

[51] Research on enzymatic hydrolysis at NREL is now broadening its focus to include research on common farm species that may be intermixed with the primary species grown.

[52] Robert H. Walker, Director, Planning and Evaluations, Alternative Feedstock Development Department, Amoco Corp., personal communication, May 1994.

## Hydrogen

Interest in hydrogen as an alternative fuel for transport has grown rapidly in recent years. Hydrogen is an extremely clean fuel that can be burned in ICES or electrochemically converted to generate electricity in fuel cells. Hydrogen can be produced from natural gas or coal: however, a more environmentally appealing idea from the perspective of $C0_2$ and other emissions is the production of hydrogen from biomass via gasification or from the electrolysis of water by using electricity generated from renewable energy.

Fuel-cycle emissions of $C0_2$ and other greenhouse gases can be reduced significantly or perhaps eliminated, depending on the source of energy used to produce hydrogen. Fuel cell vehicles that use hydrogen have essentially no tailpipe emissions apart from water vapor. The tailpipe emissions from hydrogen ICEVs are much lower than those from a comparable gasoline-powered vehicle. Emissions of CO, hydrocarbons (HCs), and particulate are essentially eliminated (traces of these gases may be emitted from combustion of lubricating oils in the engine). The only pollutants of concern are nitrogen oxides (NOx), which are formed, as in all ICES, from nitrogen taken from the air during combustion. Hydrogen vehicles probably will be able to meet any $NO_x$ standard that a gasoline vehicle can meet. In principle, an ultralean hydrogen engine could produce very little $NO_x$, and some recent work by Daimler-Benz has demonstrated near-zero emissions of $NO_x$ in hydrogen-powered test vehicles.

Environmental benefits can also be achieved by blending hydrogen with other fuels. Dual fuel operation with hydrogen and gasoline or diesel fuel can substantial] y reduce emissions of all regulated pollutants. The addition of relatively small amounts of hydrogen—as little as 5 to 10 percent by mass--can reduce CO, HC, and NO, emissions.[53] By adding 5 percent hydrogen to natural gas (the blend is called "hythane”), NOx emissions from ICEVs can also be substantially reduced.[54]

The principal barriers to widespread hydrogen use include difficult storage requirements, high production costs, and lack of a distribution infrastructure.

### *Hydrogen Storage*

Hydrogen has a very low energy density. Typical volumetric energy densities for hydrogen are 5 to 15 percent that of gasoline when stored in pressurized tanks or metal hydrides.[55] Therefore, a hydrogen-fueled vehicle requires either large on-vehicle, high-pressure storage tanks.[56] cryogenic storage,[57] or storage in another medium.[58] Factors at play in the development of hydrogen storage systems include energy densities in terms of weight and volume. safety during refueling and

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[53] Ogden et al., op. cit., footnote 17.

[54] Congressional Research Service, “Hydrogen as a Fuel.” Mar. 22,1993.

[55] *Hydrides* are special materials that absorb and hold large quantities of hydrogen. When heated, they release hydrogen gas.

56 The size of high-pressure tanks may be reduced somewhat with the introduction of advanced lightweight materials. Carbon-fiber-wrapped, aluminum-1 ined tanks allow storage at 8,000 psi, high enough for energy densities competitive with other storage methods. Carbon fiber is currently quite expensive at $50 per pound but is expected to drop in cost. The crashworthiness of such tanks, however, has not been fully determined.

[57] Storage of liquefied hydrogen would provide high energy densities. However, insulated, crashworthy tanks would have to be developed, as well as a spec i al infrastructure for handling I iqu id hydrogen. A lso, hydrogen I iquefaction is an energy - intensive process.

[58] As an example, hydrogen can be stored in the form of powdered iron. Steam from a fuel cell, for example, could be used to oxidize powdered iron m a tank onboard the vehicle, releasing hydrogen to be used as fuel. When the entire tank of iron has turned to rust, it is exchanged for fresh iron, and oxidized material could be reduced back to iron at a central facility. This is a potentially inexpensive and compact storage approach. H-Power Corporation of New Jersey is developing this technology.

in case of accidents,[59] and cost of materials and construction. Hydrogen storage requirements could be eased if vehicle propulsion systems with high efficiencies were developed. For example, by one estimate, a hybrid electric vehicle that uses a small ICE fueled by hydrogen to generate electricity could reduce hydrogen storage requirements by 50 to 65 percent compared with a pure ICEV.[60] The high efficiencies of fuel cell-based vehicles would further ease hydrogen storage problems (see discussion below). In the near term, onboard hydrogen pressure tanks could build on the experience of compressed natural gas vehicles.

### *Costs of Hydrogen Fuelel*

As shown in table 4-2, the cost of hydrogen produced from renewable sources varies considerably. On a large scale (for plants producing 50 million standard cubic feet of hydrogen per day), biomass hydrogen could cost perhaps $8 to $1 l/GJ to produce (assuming biomass costs of $2 to $4/GJ), with delivered costs of about $14/GJ (or $1.85/gal gasoline equivalent), making it the least expensive method of renewable hydrogen production.[62] Renewable electrolytic hydrogen—hydrogen produced from, e.g., wind- or photovoltaic-generated electricity-could cost anywhere from two to four times as much as hydrogen from biomass ($20 to $60/GJ), depending on advances in photovoltaic, wind, or other renewable technologies (see chapter 5). Because of their modular nature, however, electrolytic hydrogen systems could be employed at a much smaller scale than biomass gasifiers. On small production scales—which one would expect at the beginning of a transition to hydrogen or if environmental constraints limited the size of any one production area—the cost advantage of hydrogen from biomass compared to photovoltaic- or wind-powered electrolysis would likely be reduced.

On a large scale, hydrogen from steam reforming of natural gas could cost $5 to $10/GJ (with natural gas prices of $2 to $6/GJ) or 65@ to $1.30/gal gasoline equivalent. On a smaller scale (0.5 million standard cubic feet/day or 200 GJ/day), hydrogen from steam reforming could cost about $11 to $17/GJ ($1 .45 to $2.25/gal gasoline equivalent). Coal gasification plants would also exhibit strong scale economies. For large plant sizes, hydrogen from coal could cost about $10 to $14/GJ (for coal costing $1.50/GJ) or $1.30 to $1.85/gal gasoline equivalent. For a given plant size, the cost to generate hydrogen from biomass via gasification would probably be somewhat lower than the cost from coal because biomass can be gasified more quickly and at lower temperatures than coal, allowing the plant to be smaller and less capital intensive for a given output.

## Developing a Hydrogen Infrastructure

One of the key issues for development of hydrogen as a transportation fuel is that no large-scale hydrogen delivery system exists. This is unlike the situation for gasoline, electricity, or natural gas, where widespread distribution systems are already in place. Moreover, developing an infrastructure would be more difficult for hydrogen (which must be transported as a compressed gas, as a cryogenic liquid, or by pipeline) than for liquid fuels, such as methanol or ethanol, which can

[59] Many questions have also been raised about the safety of hydrogen. Although these concerns should not be dismissed, the dangers of hydrogen use have probably been overstated. With regard to flammability, hydrogen is not much different from other fuels such as gasoline and methanol. Although hydrogen would leak through mechanical fittings at a higher rate than other fuels, it disperses much more quickly and thus is less likely to form a flammable mixture. See Joan Ogden and Robert Williams, *Solar Hydrogen.. Moving Beyond Fossil Fuels* (Washington, DC: World Resources Institute, October 1989).

[60] Glenn Rambach, Lawrence Livermore National Laboratory, personal communication, Jan. 26, 1994.

[61] Cost data in this section are drawn from Ogden et a]., Op. cit., footnote 17.

[62] A delivered cost of $ 10/GJ for hydrogen has a gasoline equivalent price of $ 1.30/gal. Some recent work indicates that hydrogen might be produced from municipal solid waste for $6 to $8/GJ or 78@ to $ 1.04/gal gasoline. J. Ray Smith, Lawrence Livermore National Laboratory, personal communication, Apr. 25, 1994.

be transported and delivered to the consumer by using systcms similar to that for gasolinc.

The components of a hydrogen energy infrastructure have already been dc~'eloped. Technologies for storing. compressing. and transporting hydrogen are well known and are used in the chemical industry. The present hydrogen distribution system in the United States consists of a few hundred miles of industrial pipeline plus fleets of trucks delivering liquid hydrogen or compressed hydrigrn gas. Although about 1 EJ of hydrogen is produced in the United States per year, most of this is produced and used onsite for petroleum refining and methanol or ammonia production. Merchant hydrogen (hydrogen that is distributed) amounts to only about 0.5 percent of the total hydrogen produced and used.

Ultimate] y, the large-scale use of rewable hydrogen as a fuel would require the development of much larger hydrogen transmission and distribution systems. In the near term, hydrogen is likely to be produced from natural gas, which is presently the least expensive source. There are several ways in which the existing natural gas infrastructure could be used to bring hydrogen to consumers. First, it is possible to produce hydrogen from steam reforming of natural gas. even on a relatively small scale. Hydrogen for fleet vehicles might be produced onsite by using small-scale reformers. Alternatively, hydrogen might bc blended at concentrations up to 15 to 20 percent by volumc into the existing natural gas system and rcmoved at the point of use. At greater than 15 to 20 percent concentrations of hydrogen, changes in the distribution and retailing systems would be required because of the differing physical characteristics of hydrogen compared with natural gas.[63]

Another option for onsite hydrogen production is eletrolysis. Here. the electricity distribution system could bc used to bring offpeak power to elcctrolyzer equipment. Alternatively, standalone photovoltaic (PV) hydrogen systems could be used if the costs of PV-generated electricity decline sufficiently (chapter 5). In the longer term, as the demand for hydrogen fuel increased, central hydrogen production plants might be built. with a gaseous pipeline distribution system similar to that for natural gas.

## Electricity

Electricity may be one of the principal energy carriers for future transportation systems. Electricity has the important advantages of having an available supply infrastructure (except for home charging stations ) that is adequate now-if recharging takes place at night—to fuel several million vehicles and of generating no vehicular air emissions.[64] The latter attribute is particularly attractive to regions with severe ozone problems. Also, with the exception of some electricity imports from Canada,[65] the electricity needed to run a fleet of BPEVs would be produced domestically.

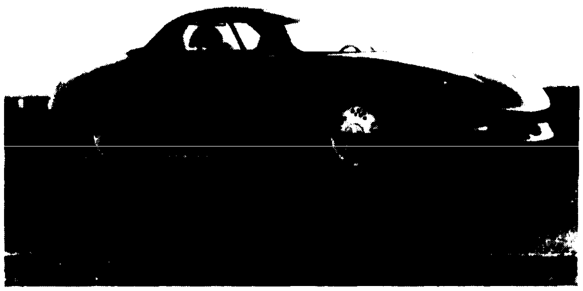
Despite virtuallly zero vehicular emissions, electric vehiclcs will have air pollution impacts because of the emissions associated with electricity production. These impacts will vary from region to region. since the power generation fuel mix varies greatly across the country. California and the northeastern United States. the two regions with the most serious pollution problems and therefore the most attractive regions for electric vehicle use. have different fuel r-nixes. California's power is generated mostly from natu -

[63] If higher percentages of hydrogen were to be used in pipelines. steps would have to be taken to prevent "embrittlement" problems. When hydrogen diffuses into pipe metal. the pipes can become brittle and crack. Embrittlement can be avoided by choosing proper pipe materials. but at a cost. *Congressional Research Service*. op. cit.. footnote 54.

[64] Over the short term. existing baseload capacity of electric utilities should be adequate to meet the demand arising from new BPEVs. If electric vehicles capture a significant share of the automobile market. however. electric utilities will be faced with significant load management challenges. See "Charging Up for Electric Vehicles," *EPRI Journal*. vol. 18. No. 4. June 1993.

[65] Some natural gas and oil imports may also be used to generate electricity

GENERAL MOTORS CORP



*General Motor's prototype two-seat electric vehicle (EV), the Impact, combines high performance (0 to 60 mph in 8 seconds) with high EV range (over 100 miles on the Federal Urban Driving Cycle).*

ral gas, nuclear, and hydropower, whereas the Northeast depends more on coal. In comparison to coal-generated electric power, electricity generated from natural gas powerplants can reduce emissions of $C0_2$, sulfur oxides, and nitrogen oxides.

Although the cost of electricity ($17/GJ at 6¢/kWh) appears high relative to gasoline ($9/GJ or $1.18/gal), the actual fuel costs for BPEVs are likely to be substantially lower than for gasoline vehicles. This savings is due principally to the efficiency advantage of electric vehicles. For example, a typical BPEV might consume about 0.25 kWh/mile. At 6¢/kWh, the operating fuel cost of the BPEV is then 1.5¢mile.[66] In practice, electric utilities are expected to offer low, offpeak electricity rates (3¢ to 4¢/kWh) to consumers for nighttime recharging of BPEVs. Thus, a typical BPEV could have operating fuel costs of less than 1 ~/mile. In comparison, the operating fuel cost for the two-seater Honda Civic del Sol is 3.7¢/mile.[67] The initial purchase cost of BPEVs, however, may be considerably higher than conventional vehicles (but may be offset by lower maintenance costs and longer lifetimes for electric vehicles; see discussion below).

With BPEVs running on renewable electricity, it would be possible to produce and use energy with very low emissions of criteria air pollutants and $C0_2$. Electricity can be produced from a variety of renewable sources such as biomass, wind energy, solar energy, and hydropower. As discussed in chapter 5, the cost of producing electricity in a "renewables-intensive utility" in the post-2010 timeframe may be comparable to that for a conventional utility (4¢ to 6¢/kWh). The primary technical issues involved in a transition toward renewable electricity-based transportation are the development of renewable electricity-generating technologies, their integration into a utility grid, and the development of BPEVs (see discussion below) and their recharging systems.

Where and when recharging takes place would influence the delivered cost of electricity for transportation. It is likely that many electric vehicles will be recharged at home during offpeak (nighttime) hours. In this case, the type of generating system used to meet offpeak demand will determine the cost and types of emissions.

Another option for electric vehicle recharging is stand-alone solar PV charging that would operate while a car was parked, for example, at work or at a commuter station. In this case, some battery storage may be needed at the PV charging station for use on cloudy days, which would add to the cost of PV electricity. The cost of electricity from stand-alone PV recharging stations would likely be higher than the cost of residential electricity from a renewables-intensive utility. Stand-alone systems might be used in settings where non-grid-connected daytime recharging is desirable or home charging is not feasible.

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[66] The California Air Resources Board projects that in the year 2000, a typical electric vehicle will consume about 0.24 kWh/mile. The General Motors Impact electric vehicle uses about 0.2 kWh/mile. See California Air Resources Board, "Emission Benefits of Electric Vehicles Relative (o ULEVS," draft, February 1994.

[67] This is based on 34 miles/gal (city) and a price of $ 1.25/gal for gasoline. Venkateswaran and Brogan, Op. cit., footnote 3.

## Some Nonrenewable Competitors

In the near term, fuels that are derived from nonrenewable sources could also offer environmental benefits. Internal combustion engine vehicles that use reformulated gasoline or compressed natural gas are likely to be formidable competitors with renewable-based ethanol, methanol, hydrogen, or electricity y. This is primarily because reformulated gasoline and CNG will likely be substantially lower in cost than renewable fuels for the near to mid-term.

### Reformulated Gasoline

Reformulated gasoline is gasoline that has been modified to have lower emissions of hydrocarbons (to reduce ozone formation), benzene, heavy metals, and other pollutants. By law, reformulated gasoline must have a 2-percent oxygen content to ensure compliance with regional CO standards. It has the advantage of not requiring engine modification or a separate fuel infrastructure. Thus, reformulated gasoline can reduce the emissions of cars already on the road.

Reformulated gasoline was first proposed as an alternative fuel in the United States in 1989 in response to the growing pressure for cleaner burning fuels, particularly the proposal by President Bush to require the sale of alternative fuel vehicles in the nine most polluted U.S. cities.[68] Subsequently, the major oil and automobile companies in the United States initiated a jointly funded multimillion dollar study to analyze the emission impacts of various reformulated blends (later expanded to include methanol and CNG) from current and future motor vehicles. Results released to date suggest that gasoline reformulation could provide modest to fairly significant emission benefits (for criteria air pollutants only; there would be virtually no reduction in greenhouse gases) at a cost of around 15¢/gal more than conventional gasoline.[69]

### *Natural Gas*

CNG can be burned in internal combustion engines with minor modifications and in diesel engines with more substantial modifications. Natural gas is a cleaner fuel than gasoline, with lower emissions of most pollutants. A dedicated CNG vehicle could have an energy efficiency about 10 percent greater than a gasoline vehicle because of its higher octane number. Natural gas ICEVs have a much shorter driving range or reduced trunk space than gasoline-fueled vehicles, however, because CNG's volumetric energy density is much lower than gasoline (about one-quarter the energy density of gasoline when compressed to the standard pressure of 3,500 psi).

The use of liquefied natural gas (LNG) could in theory overcome this range limitation. LNG is natural gas that has been liquefied by cooling it to -161 "C. The advantage of LNG over CNG is its energy density—a given volume of LNG provides about three times the vehicle range between refueling as the same volume of CNG. At least in the near term, the practical difficulties of maintaining these low temperatures, along with the high cost of containers capable of storing LNG, make LNG less promising as a fuel for light-duty vehicles. Fleet operators of heavy-duty vehicles are, however, showing increased interest in LNG.

Another major drawback of CNG as a transport fuel is the difficulty of transporting. storing, and delivering it. Because the refueling and storage systems would be similar, however, CNG vehicles might provide a bridge toward the eventual use of hydrogen, a fuel that ultimately could be derived

[68] Considerable interest in alternative fuels had already been expressed by the state of California and industry had begun responding to this interest with the development of reformulated gasoline.

[69] Some analyses indicate that if reformulated fuels were used in conjunction with electrically heated catalysts and advanced engine control technologies, CO and $NO_x$ might be reduced by as much as 50 percent. The emissions benefits would be much more modest without these vehicle modifications. See the series of technical reports produced by the Auto/Oil Air Qua] ity improvement Research Program and published by the Coordinating Research Council, Atlanta, Georgia, from 1989 to 1993.

completely from renewable sources. At present, no analysis has been undertaken to evaluate the costs and benefits of such a transition from natural gas to hydrogen.

One current incentive for switching from gasoline to natural gas is lower fuel cost, but this incentive is likely to diminish as demand for natural gas grows. The present retail price of CNG from domestic sources is about $7/GJ (in gasoline equivalent terms, about 91¢/gal without taxes or roughly comparable to gasoline when taxes are included). CNG vehicles also may have slightly lower maintenance costs than liquid fuel vehicles. The use of CNG in gasoline vehicles requires the installation of gas cylinders, high-pressure piping, and appropriate fittings to the engine. To take full advantage of CNG, the compression ratio should also be raised to about 12 to 1.[70] An automobile designed for CNG would cost about $800 to $1,000 more than a comparable gasoline-fueled vehicle, due in large part to the expensive high-pressure fuel storage equipment. This higher upfront cost is compensated partially by lower back-end costs: the storage systems probably will have a high salvage value, and the use of natural gas may increase the life of the engine and hence the resale value of the vehicle.

Natural gas will reduce HC emissions that contribute to urban smog, although it may increase $NO_x$ emissions somewhat.[71] If natural gas vehicles gain greater market penetration, they should contribute less to greenhouse gases than vehicles using petroleum- or coal-based transport fuels (see table 4-1 ). Although natural gas presents some special handling problems, it is neither toxic nor corrosive, unlike methanol and gasoline.

## EMERGING VEHICLE TECHNOLOGIES

Several technological options for improving vehicle energy efficiency and emissions are now being explored, including advanced ICEV designs and the use of new fuels in ICEVs, battery-powered electric vehicles, fuel cell electric vehicles, and hybrid vehicles (various combinations of the above).

Each of these propulsion system options could potentially play a role in bringing about a transition from the present fossil fuel transportation system to one that depends primarily on renewable energy resources.

### Advanced ICEV Designs

At present, the vast majority of light-duty vehicles on the road use gasoline-powered internal combustion engines. In recent decades, federally mandated fuel efficiency and clean air requirements have resulted in significant refinements of conventional internal combustion systems.[72] Several additional advances are likely to be introduced in coming years, including improved vehicle design and alternative fuels such as reformulated gasoline, compressed natural gas, and perhaps ethanol or methanol.

Many vehicle characteristics could be modified to improve vehicle energy efficiency:[73]

- a shift to lightweight body materials such as carbon fiber or other composites;

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[70] R. Moreno, Jr., and D. Bailey, *Alternative Transport Fuels from Natural Gas,* World Bank Technical Paper No. 98, Industry and Energy Series (Washington, DC: World Bank, 1989), p. 7.

[71] CNG vehicles can emit less carbon monoxide (perhaps 30 to 50 percent less) than gasoline or methanol vehicles, because CNG mixes better with air than do liquid fuels, and it does not have to be enriched (as much) for engine startup. The magnitude of CO reduction (and, perhaps, whether there is any reduction at all) will be determined by $NO_x$ control: if the engine has to be run slightly rich to control $NO_x$, there will be little or no reduction in CO; if it can be run slightly lean, there will be a reduction.

[72] Since 1978, fuel economy specifications have been dictated principally by federal Corporate Average Fuel Economy (CAFE) requirements. CAFE standards have been met by decreasing vehicle drag and weight, reducing engine size, and introducing fuel injection and other energy-efficient technologies.

[73] This material is drawn from and discussed in Office of Technology Assessment, Op. cit., footnote 14.

- a reduction in the vehicle aerodynamic drag coefficient;
- high-pressure, low-rolling-resistance tires;
- an advanced super-efficient engine with four or more valves per cylinder, adjustable valve lift and timing, and other low-friction or lean-burn measures; an advanced two-stroke engine; or advanced diesel;
- extensive use of aluminum and other lightweight materials in the vehicle suspension and other components (e.g., brake rotors and calipers, sway bars, wheels);
- advanced transmissions (e.g., a five- or six-speed automatic); and
- automatic engine turnoff at stops.

General Motors' new Ultralite prototype demonstrates both the potential and some of the 1imitations associated with a radical redesign of today's automobile. The Ultralite weighs 1,400 pounds (630 kg) despite being comparable in interior volume to a 3,000-pound (1,360-kg) Chevrolet Corsica; is powered by a 1.5-liter, three-cylinder, two-stroke engine that weighs 173 pounds (78 kg) yet generates 111 horsepower at 5,000 revolutions per minute (rpm); has a drag coefficient of only 0.19; and rolls on high-pressure, low-resistance tires that need no spare because they are self-sealing. Although its fuel economy at 50 mph (80 km per hour) is 100 mpg (42 km/liter), the Ultralite's Environmental Protection Agency (EPA) fuel economy rating is only 56 mpg (24 km/liter), or about 48 mpg (20 km/liter) when adjusted for on-road conditions.[74] Given the sports-car-like performance characteristics of the vehicle (zero to 60 mph in 7.8 seconds), this fuel efficiency is quite exceptional. Regardless, vehicle size and performance generally require tradeoffs with efficiency.

Vehicle energy efficiency might also be constrained by existing or new emissions and safety requirements. The need to meet certain emissions levels could affect engine performance specifications, while safety standards affect a number of design parameters including choice of materials.[75] If tractive loads (e.g., vehicle mass, aerodynamic drag, tire rolling resistance) can be safely reduced. however, engine power requirements will decline, potentially leading to a corresponding decrease in engine emissions. In this sense, there is a technical synergy between energy efficiency and emissions objectives.

To meet the new emissions standards of the amended Clean Air Act (see table 4-3), vehicles in the year 2000 will likely require onboard refueling controls, improved fuel metering and ignition, a larger or additional catalytic converter with electric heating to reduce cold-start emissions, and a larger evaporative-emissions canister. If the stricter "'Tier 2" standards are imposed by EPA, the cost of vehicle modifications may range from $200 (California Air Resources Board estimate) to $600 (Sierra Research Institute estimate) up to $1,000 (estimate of automobile manufacturers) per vehicle.[76]

To meet the ultra-low emissions vehicle (ULEV) standards established by the California Air Resources Board, gasoline vehicles may have to use dual oxygen sensors, adaptive transient control, sequential fuel injection. improved fuel preparation, improved washcoats on catalytic converters, more catalyst material (mainly palladium), double-wall exhaust pipes, air injection, and either electrically heated catalysts or close-coupled catalysts. These additions and modifications could increase vehicle cost beyond what would be required to meet federal standards.[77]

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[74] General Motors Co., brochure, n.d.

[75] The safety implications of vehicles that use advanced lightweight materials have not yet been fully explored.

[76] The cost of meeting federal Tier I standards could range from $150 to $275 per vehicle. See Sierra Research, Inc. and Charles River Associates, "The Cost-Effectiveness of Further Regulating Mobile Source Emissions." Report No. SR94-02-04. Feb. 28, 1994.

[77] The California Air Resources Board estimates that the cost of meeting ULEV requirements would be about $200 per vehicle (above and beyond the cost of meeting federal Tier I requirements). Sierra Research estimates that the cost could exceed $1.300. Ibid.

TABLE 4-3: Emissions Standards for Light-Duty Motor Vehicles (grams/mile)

| | Emissions standard | | | | | |
|---|---|---|---|---|---|---|
| Pollutant | Federal 1993 standard | Federal CAAA, Tier 1 1994 MY | Federal CAAA, Tier 2 (if needed) | CARB TLEV 1994 MY | CARB LEV 1997 MY | CARB ULEV 1997 MY |
| HC | 0.41 | 0.25 | 0.125 | 0.125 | 0.075 | 0.040 |
| CO | 3.40 | 3.40 | 1.70 | 3.40 | 3.40 | 1.70 |
| $NO_x$ | 1.00 | 0.40 | 0.20 | 0.40 | 0.20 | 0.20 |

KEY: CAAA = Clean Air Act Amendments of 1990; CARB = California Air Resources Board; HC = hydrocarbons (California regulates nonmethane organic gases, not hydrocarbons); LEV = low-emissions vehicle; MY = model year; TLEV = transitional low-emissions vehicle; ULEV = ultra-low emissions vehicle.

SOURCES: S.C. Davis and S.G. Strang, *Transportation Energy Data Book: Edition 13*, ORNL-6743 (Oak Ridge, TN: Oak Ridge National Laboratory, March 1993); and Sierra Research, Inc. and Charles River Associates, *The Cost-Effectiveness of Further Regulating Mobile Source Emissions*, Report No SR94-02-04 (Sacramento CA February 1994)

The effectiveness of proposed emissions control equipment for gasoline ICEVs is still not well known. It is not clear how far gasoline ICEV technology can be pushed to reduce emissions. In lowering emissions to meet future standards, however, ICEVs will likely become somewhat more complex and costly.

## Alternative Fuels in ICEVs: A Comparative Analysis

Conventional and advanced ICEV designs can take advantage of a number of different alternative fuels, such as reformulated gasoline, compressed natural gas, ethanol, methanol, and hydrogen. Ethanol, methanol, and natural gas vehicles are commercially available today, although in limited quantities. Demonstration hydrogen ICEVs have been built by Daimler-Benz, BMW, and Mazda and have been tested in small fleets.

Although it is difficult to project costs for technologies and fuels that have not reached large-scale production, it is nonetheless instructive to estimate these costs. The findings of one such analysis are presented here. This analysis compares the operating costs of different alternative fuels that are used in ICEVs.[78]

The reference gasoline vehicle is a year-2000 version of the 1990 Ford Taurus (26 mpg). The other vehicles are "built" hypothetically from this baseline vehicle. The travel range of these ICEVs varies from a high of about 600 km (370 miles) for the gasoline vehicle to 320 km (200 miles) for the compressed hydrogen gas vehicle. The volumetric energy density of methanol is roughly half that of gasoline but can be partially compensated by a larger fuel storage volume and the greater fuel economy (through higher compression ratio) achievable with methanol. The net result is a 20-percent lower range (485 km, 300 miles) for the methanol vehicle relative to gasoline. The range for the ethanol vehicle (565 km, 350 miles) is greater than for methanol because ethanol has an energy density about 25 percent greater than methanol. The CNG range is assumed to be less than that of the methanol vehicle because CNG at 3,000 psi has roughly half the energy density of methanol.

[78] The reader should not view this analysis as an attempt at a definitive cost projection, but rather as a scenario analysis—an "if-then" statement. The analysis was performed by and detailed in Odgen et al., op. cit., footnote 17.

**TABLE 4-4: Analysis of Baseline Cost Results for ICEV Systems (1991 dollars)[a]**

| Item | Gasoline | MeOH | EtOH | CNG | Liquid $H_2$ | Hydride $H_2$ | Compressed $H_2$ |
|---|---|---|---|---|---|---|---|
| Fuel retail price, excluding taxes (*$/gal gasoline equivalent*)[b] | 1 18 | 185 | 152 | 0.96 | 363 | 1.54 | 1 79 |
| Full retail price of vehicle including taxes ($)[c] | 18,000 | 17900 | 17,900 | 19,500 | 20,200 | 24,200 | 24550 |
| Levelized annual maintenance cost ($/year) | 396 | 392 | 392 | 370 | 392 | 392 | 392 |
| Total life-cycle cost[d] (¢/km) | 21 | 223 | 214 | 205 | 263 | 244 | 246 |
| Break-even gasoline price ($/gal)[e] | n.a. | 204 | 1 64 | 1 26 | 369 | 291 | 297 |

[a]The cost estimates for the gasoline ICEV are detailed in M A DeLuchi *Hydrogen Fuel Cell Vehicles* UC D- ITS-RR-92- 14 (Davis CA Institute of Transportation Stales University of California at Davis September 1992) The cost estimates for the alternative-fuel ICEVs are based primarily or data summarized in D A Sperling and M A De Luchi *Alternative Transportation Fuels and Air Pollution*, report to the OECD Environment Directorate (Paris France Organization for Economic Cooperation and Development March 1991)

[b]Dollars per gasollne-equivalent gallon is calculated as the price of the fuel to the motorist (dollars per million Btu), *excluding* federal state and local taxes (31 ¢ gal in the United States) multiplied by O 125 million Btu gal of gasoline Note that this gasoline equivalence is defined in terms of energy delivered 10 the vehicle and hence does not account for the efficiency with which the vehicle uses that energy The estimate of the cost of gasoline assumes a world 011 price (post 2000 timeframe) of $2640, per barrel and reformulated gasoline of 15¢/gal more than conventional gasoline

[c]Including sales tax dealer costs and shipping costs

[d]Includes federal state and local taxes of O 78¢ km fOr all vehicles

[e]The retail price of gasoline (including federal and state taxes in the United States) at which the life-cycle consumer cost perkilometer of the alternative fuel vehicle would equal that of the gasoline vehicle

KEY EtOH ethanol MeOH methanol n a not applicable

SOURCE Joan M Odgen et al A Technical and Economic Assessment of Renewable Transportation Fuels and Technologies " report prepared for the Off Ice of Technology Assessment May 1994

The lifetimes for all vehicles are assumed to bc the same, except for the CNG vehicle. A CNG vehicle's lifetime is assumed to be slightly longer than that of a gasoline vehicle because some evidence suggests that CNG might cause less engine wear than gasoline.[79] The weights of liquid-fueled vchicles (gasolinc. methanol, ethanol, and liquid $H_2$) are all comparable—about 1,400 kg (3,000 pounds). The gas-fueled vehicles (CNG and compressed $H^2$) arc somewhat heavier because of the weight of compressed gas cylinders. The drag coefficients arc assumed to be the same for all vehicles except the hydrogen-fueled system. The very low energy storage density of the latter demands a more streamlined design in order to achieve a reasonably acceptable driving range, Because their engines would have higher compression ratios, the fuel efficiencies of the methanol, ethanol, CNG, and hydrogen vehicles would be higher than that of the gasoline vehicle (about 7 percent higher for CNG and 15 percent higher for methanol, ethanol, and hydrogen).

Table 4-4 shows the projected retail vehicle price, fuel price, and total life-cycle costs per kilometer for the ICEV-fuel combinations considered here. The retail fuel prices correspond to those shown in table 4-2. The ethanol, methanol. and hydrogen fuel costs assume production from bio-

[79]The relationship between engine lifetime and vehicle lifetime, however, is complex.

mass, although it is unlikely that large quantities of fuel from biomass will be available before2010 under current policy. The full retail prices of all liquid-fueled ICEVs are comparable. The CNG vehicle cost is about $1,500 higher. The hydrogen ICEV (compressed gas or hydride storage) is about $6,000 higher. The hydrogen and CNG vehicles are more costly principally because of the relatively expensive storage equipment involved.

Ownership and operating costs can be combined and expressed as a total cost per kilometer over the life of a vehicle by amortizing the initial cost at an appropriate interest rate, adjusting for salvage values and vehicle life, and adding periodic costs such as maintenance, fuel, insurance, and registration. Table 4-4 projects this total levelized life-cycle cost per kilometer of travel for each fuel category. (Externality costs, such as the costs of emissions, are not included in this analysis.) The baseline gasoline vehicle costs 21 ¢/km. Among ICEVs, the CNG vehicle has a slightly lower cost, whereas ethanol and methanol have slightly higher costs. The hydrogen ICEV would be the most expensive, at 17 to 25 percent higher than the gasoline ICEV.

In addition, table 4-4 provides life-cycle costs in terms of the break-even gasoline price. This is the retail price of gasoline (including taxes) at which the life-cycle cost per kilometer for the gasoline ICEV would be the same as that for the alternative vehicle under consideration. The break-even price ranges from $1 .30/gal ($9.86/GJ) for the CNG vehicle to about $2/gal ($15/GJ) for the methanol vehicle and nearly $3/gal ($23/GJ) for the compressed $H_2$ vehicle.

Again, many of the important cost parameters are very uncertain, particularly the costs of delivered fuel from biomass (or fossil fuels), some fuel storage technologies (e.g., hydrogen storage), and some vehicle technologies. A sensitivity analysis of the basic assumptions use'd in these calculations indicates that if one of several important cost parameters is overly optimistic, the life-cycle cost and break-even gasoline price could increase substantially.[80]

## | Battery-Powered Electric Vehicles

Interest in electric vehicles has surged and ebbed several times during this century. In the past few years, there has been increasing awareness of the potential for advanced BPEVs to provide substantial air quality and petroleum conservation benefits. A cost-effective, high-performance battery-powered electric vehicle, recharged quickly by solar or biomass-derived power, would be an attractive transportation option.

At present, however, no existing battery technology would allow a pure BPEV to be competitive with petroleum-based vehicles. The energy densities of all battery systems available even in prototype form today are on the order of 100 times lower than those of gasoline.[81] This means that a given amount of gasoline contains enough energy to propel a car much further than the same weight or volume of batteries. The greater effi-

[80] Odgen et al., op. cit., footnote 17.

[81] The energy density of gasoline is 340 times greater than that of a lead-acid battery system per unit of weight and 120 times greater per unit of volume (energy density for gasoline= 12,000 Wh/kg; and for lead-acid batteries 35 Wh/kg). For an electric vehicle (EV) powered by lead-acid batteries to have a 300-mile (480 km) range (assuming the EV uses 0.24 kWh/mile), more than 4,500 pounds (2,000 kg) of lead-acid batteries would be required. If the projected energy densities of some advanced batteries can actually be achieved, however, this weight figure could be reduced by a factor of three or four (e.g., lithium polymer battery). It should also be noted that specific energy (watt-hours per kilogram) (ends to have an inverse relationship to specific power (power density determines top speed and acceleration). Thus, it is not now possible to maximize a battery's energy and its power simultaneously, a limitation that may require an EV (o have two power sources to achieve acceptable range and acceleration (e.g., either two batteries or a battery and an ultracapacitor). See "The Great Battery Barrier," *IEEE Spectrum*, November 1992, pp. 97-101.

ciency of an electric drivetrain compared with an ICE drivetrain compensates only partially for this energy density disparity[82] (see figure 4-3).

Batteries are also expensive, and thus battery characteristics are the principal determinants of both the initial and the life-cycle operating costs (total cost per mile) of BPEVs. These costs maybe offset somewhat by the relatively high efficiency of electric drivetrains. In addition, some analyses of BPEVs assume that the use of an electric drivetrain will result in lower maintenance costs and longer vehicle life.[83] If true, BPEV life-cycle costs would decrease further, perhaps allowing them to become economically competitive with ICEVs.[84] There is, however, much uncertainty regarding these assumptions. For example, because of battery life limitations, particularly in frequently cycled systems, electric vehicle maintenance and battery replacement costs may turn out to be higher than currently assumed.

Mass production may bring down battery costs, but many of the more advanced batteries under development incorporate expensive materials, as well as sophisticated engineering techniques in their construction. Lead-acid batteries for the experimental electric vehicle that General Motors expects to produce are likely to cost at least $2,000 and last for 15,000 miles (24,000 km), probably less that two years.[85] This would mean spending more than $12,000 on batteries over a 100,000-mile ( 160,000-km) vehicle life. The nickel-iron battery packs for the Chrysler electric minivan (the TEVan) cost more than $6,000 but are projected to last up to 75,000 miles (120.000 km).[86] The nickel-metal hydride battery under development by Ovonic Battery is projected to cost $5,000, with a life of more than 100.000 miles (160,000 km).[87]

The principal R&D challenge for BPEVs is to develop a battery that has high energy density for range, high power density for acceleration performance, reasonable longevity, and low cost[88] and is quickly rechargeable,[89] safe, and readily recy -

[82] Other advances such as regenerative braking (electric motors on the wheels are used to recover braking energy) will further improve electric drivetrain efficiency. It should be pointed out, though, that the actual in-use efficiency of electric drivetrains has some areas of uncertainty. Thus far, there has been little real-world testing. The greatest uncertainty is battery cycle efficiency, which could vary anywhere from 60 to 90 percent. "Smart" charging could help ensure high battery efficiencies. See "'Batteries Charged Quickly, Electric Truck Sets Record," *New York Times*, Feb. 16, 1994, p. D2.

[83] See, e.g., M. Delucchi, Institute of Transportation Studies, University of California-Davis, "Hydrogen Fuel-Cell Vehicles," Sept. 1, 1992.

[84] Because of the energy density limitations of current battery technology, however, BPEVs would probably not be competitive in terms of range; they could have acceleration characteristics comparable to ICEVs.

[85] A recently announced improved lead-acid battery design could greatly extend battery life. Electrosource, Inc. has developed a lead-acid battery that uses a "woven lead mesh" instead of heavy lead plates. A lead wire grid is wrapped around a fiberglass core. This construction apparently enables the battery to withstand more charge-d if charge cycles. Electrosource believes that the battery might be able to last about 80,000 miles ( 130,000 km), but this has not been demonstrated. The battery is currently being tested by Argonne National Laboratory. See "Producing the Near-Term EV Battery," *EPRI Journal*, April/May 1994, pp. 6-13.

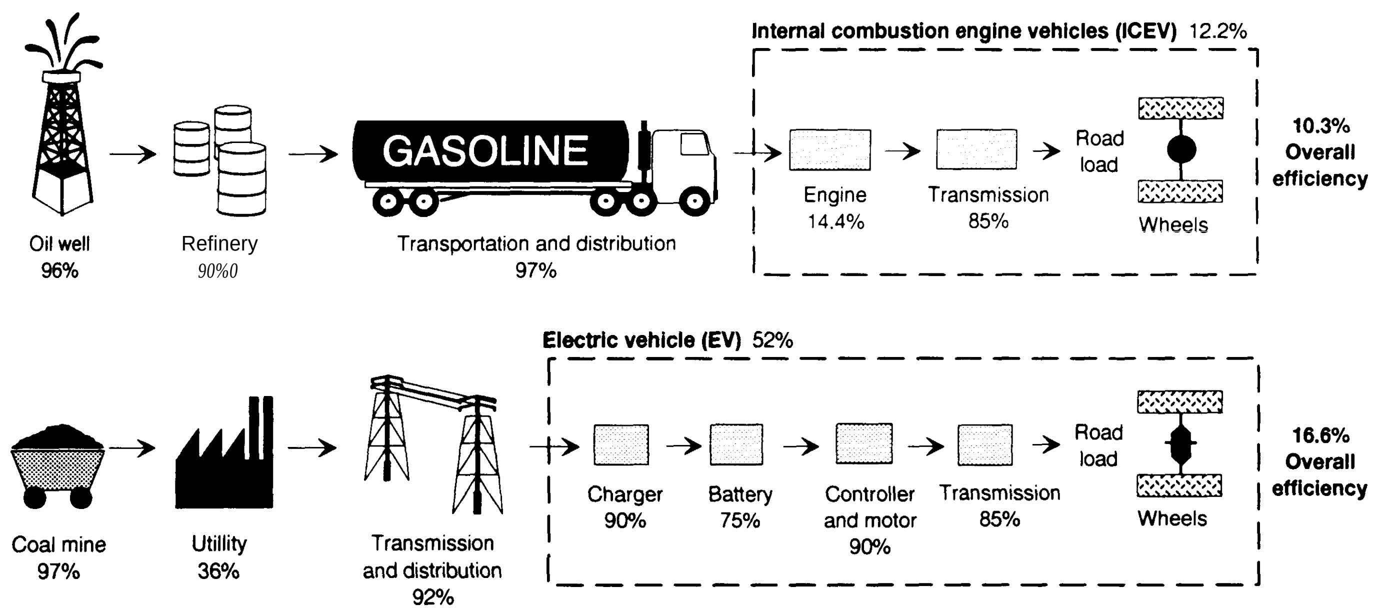
[86] Chrysler Corp., brochure, May 1992.

[87] The potentially long operating life of the nickel-metal hydride battery has not yet been demonstrated. Venkateswaran and Brogan, op. cit., footnote 3.

[88] The mid-term cost goal of the Department of Energy-U.S. Advanced Battery Consortium R&D program is $150/kWh. This implies a cost of $6,000 for a 40-kWh battery pack for a typical electric vehicle. Achievement of these cost goals can be validated only in pilot production, which is still several years away. Ibid.

[89] A "quick" recharge system (e.g., 15 minutes) could be quite costly because of the requirement for a high energy input in a short Period of time. One recently announced quick recharge system requires about 440 volts and 160 amperes. which is currently not available to homes or marry businesses. Such a recharge requirement raises a number of peak capacity and infrastructure issues. See Roberta Nichols, "The United States Advanced Battery Consortium: Making Longer Life Batteries Affordable." in *Proceedings of the International Conference on the Urban Electric Vehicle* (Stockholm, Sweden: Organization for Economic Cooperation and Development, May 1992), pp. 347-354.

FIGURE 4-3: Drivetrain Efficiencies




NOTE: An electric drivetrain can be three to four times as efficient as a mechanical ICE drivetrain (e.g., 52 percent for electric vehicles (EVs) versus 12 percent for ICEVs). This efficiency differential drops substantially when the overall fuel chain efficiency for ICEVs and EVs is taken into consideration (16.6 percent for coal-powered EVs versus 10.3 percent for gasoline-powered ICEVs). The fuel chain efficiency for EVs could be much higher if new power generation technologies are deployed. Advanced coal plants might achieve efficiencies close to 50 percent, while efficiencies of 60 percent are possible for advanced natural gas plants. With an advanced natural gas plant the overall fuel chain efficiency for EVs could rise to 27 percent.

SOURCE: John Brogan and S. Venkateswaran, "Diverse Choices for Hybrid and Electric Motor Vehicles," in *Proceedings of the International Conference on Urban EVs* (Stockholm, Sweden: Organization for Economic Cooperation and Development, May 1992).

TABLE 4-5: Technical Objectives of the U.S. Advanced Battery Consortium[a]

| | Mid-term | Long-term |
|---|---|---|
| Specific energy (Wh/kg) | 100[b] | >200 |
| Energy density (Wh/liter) | 135 | >300 |
| Specific power (W/kg) | 150 | >400 |
| Power density (W/liter) | 250 | >600 |
| Life (years) | 5 | 10 |
| Life (cycles to 80% discharge) | 600 | 1,000 |
| Cost ($/kWh) | <$150[c] | <$100 |
| Operating temperature range (°C) | -30 to 65 | -40 to 85 |
| Recharge time (hours) | 6 | 3 |

[a] Some of the battery technologies being pursued include nickel-metal hydride, lithium polymer, nickel-zinc, nickel-iron, zinc-air, lithium-iron disulfide, and sodium-sulfur.

[b] Current lead-acid batteries have a specific energy density of 35 to 45 Wh/kg.

[c] A goal of $150/kWh implies a cost of $6,000 for a 40-kWh battery pack for a typical electric vehicle. If the typical electric vehicle consumes 0.2 kWh/mile, then a 40-kWh battery pack would provide a range of 200 miles (320 km).

SOURCE U S Advanced Battery Consortium

clable. No battery yet exists that meets all these criteria. As a consequence, the federal government is leading a public-private sector consortium to address fundamental battery technology barriers. Table 4-5 lists the technical objectives of the Department of Energy -U.S. Advanced Battery Consortium.

Motors and control systems have improved greatly in recent years with advances in materials technology and power electronics,[90] so that the energy efficiencies of many electric drivetrain components are well over 90 percent. Total efficiency is much less, however, when components must be used together. Therefore an R&D program must include components and systems integration.

As discussed earlier, electric vehicles have essent i ally no direct emissions and therefore may alleviate urban air quality problems. Widespread use of BPEVs could greatly reduce CO and hydrocarbon emissions in particular. The overall contribution to pollution depends on the nature of the electricity generation process. Electricity generated from a coal-fired powerplant will contribute significantly to local and global pollution.[91] If vehicles were powered by electricity from renewable energy sources, however. both $C0_2$ and criteria pollutant air emissions could be largely eliminated. In any case, electric vehicles may contribute less to urban air pollution since powerplants are frequently located outside urban areas.

[90] For example, advances in microelectronic have resulted in low-cos[, lightweight direct current (de) to alternating current (ac) inverters, which make it attractive to use ac (or brushless dc) rather than conventional dc motors. With the improved inverters the entire ac system is cheaper, more compact, more reliable, easier to maintain, more efficient, and more adaptable to regenerative braking than the dc systems used in virtually all BPEVs (o date, Ogden et al., op. cit., footnote 17.

[91] It should also be pointed out that upstream emissions associated with gasoline refining can be considerable. For example, emissions of VOCs associated with gasoline production are much greater than those associated with electricity production for EVs. See M.A. Delucchi, "Emissions from the Production, Storage, and Transport of Crude Oil and Gasoline," *Journal of the Air and Waste Management Association,* *vol. 43, 1993,* pp. 1486- 1495: and Q. Wang et al.. "Emissions Impacts of Electric Vehicles," *Journal of the Air and Waste Management Association*, vol. 40, *1990, pp. 1275-1284.*

Battery-powered electric vehicles may pose an environmental hazard unique among the alternative fuels. The batteries required by electric vehicles typically have short lifetimes and may present a disposal problem. The battery technologies under development also require special disposal procedures for production wastes as well as for spent batteries. Battery recycling and disposal issues have been incorporated into the program objectives of the U.S. Advanced Battery Consortium.

## Fuel Cell Vehicles

Among the many propulsion systems in existence or under development, fuel cell-powered vehicles could perhaps take the most advantage of' a well - developed renewable fuel supply. Spurred in part by the emerging market for zero-emission vehicles, and partly by recent advances in fuel cell technology, fuel ceil-powered vehicles have been the subject of growing at tent ion. Fuel cell vehicles are of particular interest because they could potentially combine the best attributes of BPEVs—zero or near-zero vehicle emissions, high efficiency, quiet operation, and long life—with the long range and fast refueling time of ICEVs.

Like batteries, fuel cells arc electrochemical devices. In a battery, the electricity-producing reactants are regenerated during recharging: in a fuel cell, the reactants are supplied continuously from an external source (e.g., a hydrogen storage tank plus air). Fuel cells convert the chemical energy in a fuel (e.g., hydrogen or a hydrogen carrier such as methanol) and oxidant (usually oxygen in air) directly into electrical energy. Since fuel cells produce electricity without combustion, higher energy efficiencies are possible, and air pollution is virtually eliminated.

The efficiency of a fuel cell (electrical output divided by fuel input) can be higher than that of heat engines. Practical efficiencies of 40 to 60 percent are possible for fuel cells, which is considerably higher than an internal combustion engine in the sizes appropriate for vehicles (the typical gasoline engine achieves peak efficiencies of about 30 percent). When integrated into vehicle systems. the efficiency differential between fuel cells and ICES will change somewhat depending on the type of vehicle technology employed.

For example, if an ICE is used in a hybrid configuration with a battery and an electric drive train, the intrinsic efficiency gap between fuel cells and engines may be reduced by about half.[92] Fuel cell vehicles could, however, have 2 to 3 times the overall energy efficiency of conventional gasoline-powered ICEVs for a typical urban driving cycle.[93] The efficiency of an ICEV over the EPA urban driving cycle ranges from 12 to 15 percent .[94] FCVs should be capable of achieving overall systems efficiencies of 30 to 40 percent.[95]

Several types of fuel cells are now under development. These include the proton-exchange

[92] See J. Ray Smith, "The Hydrogen Hybrid Opt ion," paper presented at the Workshop on Advanced Component\ for Electric and Hybrid Electric Vehicles, Gaithersburg, MD, Oct. 27-28, 1993.

[93] In contrast to an ICE, the fuel cell system has higher efficiency at the lower end of its load range. This is particularly favorable for urban driving conditions. Some estimates indicate that the per-mile energy usage of passenger fuel cell vehicles (FCVs) would be about half that of comparable conventional vehicles. Variable valve and cylinder deactivation technologies now under development by some manufacturers may reduce low power inefficiencies in conventional ICEVs and narrow this FCV advantage. For FCV performance and cost projections, see Allison Gas Turbine Division, op. cit., footnote 20.

[94] Some estimate that this 12 to 15 percent range could be pushed to more than 20 percent with the use of an optimized drivetrain, which would not be prohibitively expensive. John DeCicco, American Council for an Energy-Efiicient Economy, personal communication, June 16, 1994. On the highway, where an engine can operate at constant speed, a 25-percent energy efficiency can be achieved. Smith, Op. cit., footnote 92.

[95] The 30 to 40 percent figure assumes a fuel cell efficiency of 45 to 50 percent, a fuel reforming efficiency of 80 to 90 percent (for the conversion of methanol to hydrogen), and an efficiency of 80 to 90 percent for the controller and electric motor. Regenerative braking is not assumed here.

membrane cell (PEM), the phosphoric acid cell, the alkaline cell, and the solid oxide cell. Among these options, many researchers believe that PEM fuel cells are the best suited for use in highway vehicles in the mid-term. Compared with other types of fuel cells, PEM cells are relatively light and compact and have the advantages of high power density, quick startup time, low operating temperature (80° to 100°C or 176° to 212°F) and potentially greater longevity. Phosphoric acid cell technology is perhaps the most mature, but it is too bulky for light-duty vehicle use.[96] Alkaline fuel cells perform comparably to PEM cells and have lower material costs, but they have extremely long startup times (up to 2 hours) and require a $CO_2$-free air supply to prevent poisoning of the cell electrolyte. Solid oxide cells potentially offer the greatest power densities but operate at very high temperature (800° to 1,OOO°C or 1,500° to 1,800°F), require extremely sophisticated fabrication techniques, and are far from commercialization. Thus, most light-duty vehicle demonstration programs today are planning to use PEM fuel cells.

In a PEM fuel cell, hydrogen is delivered to the anode and oxygen (or air) to the cathode. The anode and cathode are separated by a thin polymer membrane that conducts protons (hydrogen ions) but not electrons.[97] At the cathode, hydrogen separates into hydrogen ions and electrons in the presence of a platinum catalyst.[98] The electrons move through an external circuit, driving the motor. Hydrogen ions are conducted through the membrane, where they combine with the returning electrons and oxygen to form water, which is removed from the cell. Overall, the fuel cell combines hydrogen and oxygen to produce electricity y, heat, and water.

In addition to the engineering of the cell itself, an important challenge to designers of fuel cell propulsion systems is the means of storing the hydrogen fuel. As discussed earlier, hydrogen could be stored directly onboard the vehicle in high--pressure tanks, released in reaction with sponge iron, or produced onboard via reforming of a hydrogen carrier such as methanol, ethanol, or methane. Although onboard reforming adds complexity and weight to a fuel cell propulsion system, it probably represents the most viable fueling option since it allows the greatest vehicle range.

Methanol is perhaps the easiest to reform onboard the vehicle, because relatively modest temperatures are needed (300°C (570° F) or less) .99 Reforming of ethanol requires temperatures around 500°C (900°F) and some analysts suggest that will be a major disadvantage. It is not clear, however, whether an ethanol-fueled system would be prohibitively more complex than a methanol-fueled system.[100] Because the energy density of ethanol is about 25 percent higher than that of methanol (allowing greater vehicle range) and because ethanol is less corrosive and toxic, the

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[96] The phosphoric acid fuel cell is considered a near-term option for heavy-duty vehicles. A phosphoric acid cell is currently being used in the Department of Energy's fuel cell bus demonstration program.

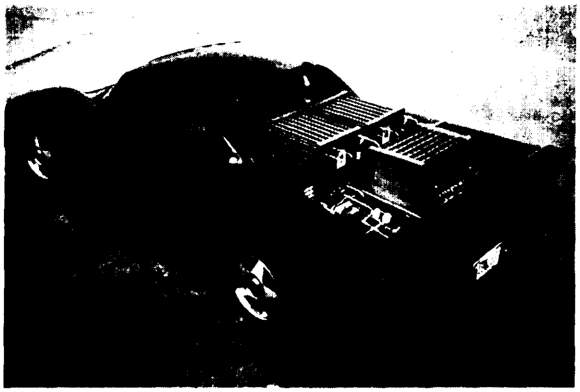
[97] A sing le membrane-electrode sandwich is about four-hundredths of an inch thick. A fuel cell stack is assembled by placing one membrane-electrode sandwich on top of another.

[98] Because the platinum catalyst is poisoned by CO, hydrogen for PEM fuel cells must contain no more than a few parts per million of CO. This imposes stringent cleanup standards on hydrogen produced via natural gas reforming.

[99] Researchers are also investigating the direct use of methanol in fuel cells (i.e., introduction of methanol fuel directly to the fuel cell anode). This would eliminate the need for an onboard reformer and could substantially reduce system complexity and cost. The technical challenges facing direct methanol fuel cells appear, however, to be significantly greater than those for hydrogen fuel cells. Michael Krumpelt, Argonne National Laboratory, personal communication, January 1994.

[100] Both methanol and ethanol are reformed at temperatures well above the operating temperature of the PEM cell. In either case. the reformate must be cooled and treated to remove CO. Thus the higher temperature of the ethanol reformer may not add much to the complexity and cost of the system. Romesh Kumar, Electrochemical Technology Program, Argonne National Laboratory, personal communication, Jan. 31, 1994.

ENERGY PARTNERS, INC



*Energy Partners of West Palm Beach, Florida, is developing a prototype PEM fuel cell vehicle dubbed the "Green Car" The prototype is fueled by compressed hydrogen*

reforming of ethanol for fuel cell vehicles is currently the subject of an R&D program funded by the Department of Energy (DOE). Methane reforming requires temperatures around 800°C (1 ,500°F). In the future, if solid oxide fuel cells are developed for transportation. methane or ethanol could be readily used because of the high operating temperature of the cells (800° to 1,000°C or 1 ,500° to 1 ,800" F).

A number of experimental PEM fuel cell vehicles are now under development.[101] The fuel cell vehicle is an electric drive vehicle that uses a fuel cell system in place of (or, in some designs, in parallel with) a rechargeable storage battery (see figure 4-4). The fuel cell system consists of a fuel cell stack, which produces the electricity; an air compressor to provide pressurized air to the fuel cell; a cooling system to maintain the proper operating temperature; and a water management system to keep the PEM membrane saturated and remove water as it is created at the cathode. If the fuel is stored as methanol or ethanol, a reformer is needed on the vehicle to convert the fuel to hydrogen.

In theory, all the power demands in an FCV can be provided by a fuel cell alone. The most practical implementation of fuel cells in vehicles, however, might involve designing a fuel cell to meet the "baseload" power requirement and using a peak power device to meet demands for quick acceleration. The peak power device could be a storage battery, an ultracapacitor,[102] or a flywheel.[103] Such a design approach could be quite important since methanol reformers cannot follow rapid load changes (unlike a fuel processor, batteries or ultracapacitors can more readily follow the load profile). Such a storage device could provide initial power during the fuel cell system warmup and also allow energy to be recovered from regenerative braking. Since most vehicles spend the vast majority of the drive cycle at low load where the fuel cell alone would be adequate, the peak power device could have a low storage capacity coupled with a high power density.

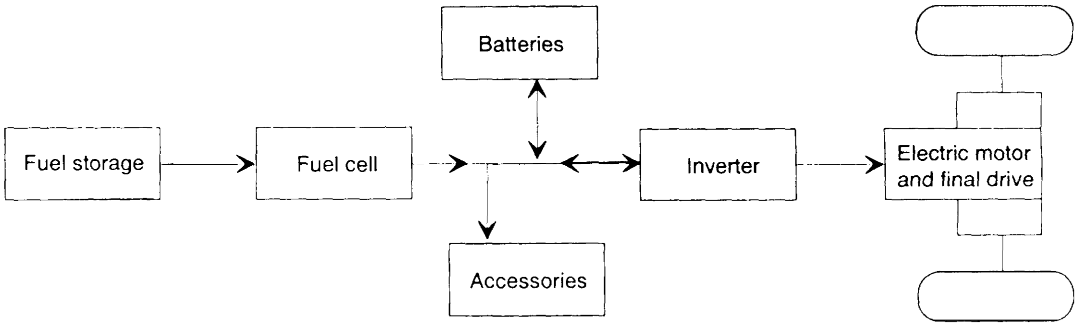
The overall environmental impact of a fuel cell vehicle will depend on the means of production and delivery of the hydrogen or hydrogen carrier

[101] DOE is now operating a demonstration fuel cell bus with onboard methanol reforming. DOE is also involved in a joint project with General Motors and other industrial partners to demonstrate a PEM fuel cell automobile (with onboard methanol reforming) by the turn of the century. Daimler-Benz recently unveiled a prototype PEM fuel cell van using high-pressure hydrogen storage. Energy Partners in Florida has recently unveiled its prototype "Green Car, " a hydrogen-powered PEM fuel cell automobile. Mazda and Seimens are also developing PEM fuel cell vehicles. However, commercial production of these prototypes is still many years away.

[102] Capacitors store electric charge on metal surfaces separated by thin layers of insulator. Recent developments in materials technology, including the creation of aerogels—very light porous solids—allow the creation of substances with very large surface area compared with their volume, which makes them suitable for the construction of capacitors capable of storing and quickly delivering particularly large amounts of charge. Such devices are called ultracapacitors.

[103] Flywheels are in essence "electromechanical" batteries. A rapidly spinning rotor is used to store energy, which is then tapped electromagnetically. The principle of storing energy in a rotating wheel is an old one—potters use it, and many combustion motors employ a flywheel to smooth out fluctuations in their output-but new technology allows rotation speeds far greater than that possible with conventional steel-rimmed wheels. Modem flywheel rotors use advanced composite materials that are light and strong, and have very high energy densities because they spin so fast (up to 2,000 revolutions a second). See Michael Riezenman, "A Different Spin on an EV Battery," *IEEE Spectrum*, November 1992, p. 100.

FIGURE 4-4: Advanced Fuel Cell Vehicle Power Train Configuration




NOTE: In a fuel cell vehicle, fuel (e.g., methanol) is converted to dc electricity by the fuel cell. This energy is directed into the batteries or to the inverter depending on instantaneous demand. The inverter controls power flow to the electric motor(s) that propels the vehicle. This configuration allows the vehicle to be powered by the battery alone, the fuel cell alone, or a combination of both. The control strategy employed allows for intelligent load sharing between the fuel cell and the battery, depending on the driving requirements and state of charge of the batteries.

SOURCE: Allison Gas Turbine Division, "Research and Development of Proton-Exchange Membrane (PEM) Fuel Cell System for Transportation Applications: Initial Conceptual Design Report," EDR 16194, paper prepared for the Office of Transportation Technologies, U.S. Department of Energy, Nov. 30, 1993.

used. Just as BPEVs can offer significant environmental benefits if they are recharged by using renewably generated electricity, FCVs could have very low overall emissions if hydrogen or hydrogen fuel carriers were derived from renewable sources. If FCVs were to use hydrogen. methanol, or ethanol made from biomass, $CO_2$ emissions could be reduced by more than 90 percent compared with a gasoline ICEV (see table 4-1). It should be noted that fuel reforming does produce $CO_2$, but if renewably grown biomass is the fuel source, the global carbon budget would not be affected. The use of hydrogen produced from electrolysis of water using solar-generated electricity would virtually eliminate $CO_2$ emissions for the entire fuel cycle.

Despite their promise, large-scale commercial production of fuel cell vehicles is still many years or even decades away.[104] Many key vehicle technologies are still in the developmental phase. Although some advances have been made in the area of PEM fuel cell performance, much progress is required before a complete fuel cell system can be packaged for an automobile. The integration of different system components will be a formidable engineering undertaking. For example, if an onboard reformer is used, sophisticated thermal control equipment is required. The long-term reliability of the essential components of a fuel cell system has not yet been demonstrated in an automotive environment or over a typical automotive duty cycle.[105]

The costs of PEM fuel cell components must be reduced, in some cases, by orders of magnitude. Although fuel cell costs will likely decrease as

[104] The PEM fuel cell prototype vehicle being developed jointly by DOE and General Motors (Allison Gas Turbine) will not be completed until 1999 or 2000. Even if the prototyping effort is successful, it will take years of engineering refinement before mass production can begin.

[105] See Philip J. Haley, Chief Project Engineer, Vehicular Engines, Allison Gas Turbine Engine Division, testimony at hearings before the House Committee on Science. Space, and Technology, Subcommittee on Energy, July 20, 1993.

## BOX 4-2: Fuel Cell Vehicle R&D Challenges

Many technical and economic barriers need to be overcome before the fuel cell vehicle becomes a viable competitor with other vehicle technologies. The main R&D issues facing fuel cell vehicles are:

- Development of proton-exchange membrane (PEM) fuel cells
  1. Reducing the cost and iImproving the performance of the polymer membrane without compromising its mechanical properties or making it more sensitive to impurlhes in the gas streams. At present, the cost of the membrane is the single largest contributor to the cost of the PEM fuel cell. Current costs for the membranes are about $1 ,000/kg, largely because these materials are custom manufactured in small quantities, Membrane costs need to be brought down to around $1 O/kg,
  2. Mass producing large-area fuel cell stacks with low platinum catalyst loadings, Platinum requirements have been greatly reduced (by fortyfold) in small-area laboratory fuel cells These advances need to be achieved for large-area fuel cell stacks as well
  3. Finding a simple and effective way to keep the membrane moist, while still removing product water at the cathode
  4. Developing a membrane that withstands temperatures of 150°C (300° F), This would allow methanol to be oxidized directly, thus obviating the need for a platinum catalyst.
  5. Reducing the size and energy consumption of the air compression system
  6. Reducting the weight, bulk, and cost of the fuel cell stack components and assembly
- Development of low-cost, compact, simple, and reliable fuel cell system auxiliaries.
- Development of electric drivetrains designed for long-range, high-efficiency, high-power, and rapid transient operation.
- Development of control systems for fuel cell vehicles, which can coordinate the use of fuel cell and peak power devices.
- Development of batteries or other peak power devices suitable for use in fuel cell vehicles, The characteristics required differ from those for battery-only powered electric vehicles.
- For hydrogen fuel cell vehicles, development of lightweight, low-cost, high-pressure compressed gas cylinders for onboard hydrogen storage.
- For methanol fuel cell vehicles, the development of onboard reformers with rapid response time, Methanol reformers today have long warmup times and cannot follow rapid load changes

SOURCES Joan M Odgen et al , "A Technical and Economic Assessment of Renewable Transportation Fuels and Technologies, " report prepared for the Office of Technology Assessment, May 1994 and Michael Krumpelt, Argonne National Laboratory, personal commumcation, January 1994

economies of scale are achieved in manufacturing,[106] the reductions necessary to make FCVs competitive with other vehicle options will require intensive R&D in coming years.[107] Some of the major R&D challenges are enumerated in box 4-2. If mass production is able to bring down component costs and if major system integration challenges are met, some estimates indicate that it may be possible for FCVs to have life-cycle operating costs comparable to conventional gasoline ve-

106 As manufacturing ramps up, many products typically follow a "learning" or "experience" curve, where costs decline 20 percent with each doubling of production. See Linda Argote and Dennis Epple, "Learning Curves in Manufacturing," Science, vol. 247, Feb. 23, 1990, pp. 920-924.

107 A recent study estimates that a mass-produced FCV power system could cost as little as $50/kW. See Allison Gas Turbine Division, Op. cit., footnote 20.

hicles.[108] This is due principally to the high efficiencies and longer lifetimes possible with FCVs.[109] Many essential technologies, including the fuel cell itself, are still many years away from commercialization, however, and thus cannot be firmly costed. Consequently, such estimates should be treated cautiously.

## Hybrid Vehicles

Given the technical difficulties confronting both battery-powered electric vehicles and fuel cell electric vehicles, researchers have been exploring the possible advantages of hybrid electric vehicles. Hybrid systems could provide many of the energy efficiency and emissions benefits of pure BPEVs, while offering greater flexibility with respect to range and performance. In the broadest sense, hybrid propulsion systems combine two power sources. The range of potential sources includes batteries, flywheels, internal combustion engines, gas turbines, fuel cells, and diesel engines.

One emerging hybrid concept is to use electric motors to drive a vehicle's wheels, with the motors powered by an electrical storage system that is recharged by a low-power internal combustion engine (the ICE drives an electric generator).[110] The combustion engine would run only when the electrical storage device needed recharging and would operate at a constant speed to maximize efficiency.[111] The electrical storage device could be a battery, ultracapacitor, or advanced flywheel, and could be used to recover energy currently lost during the braking cycle, thereby reducing total fuel consumption. Because the ICE would be small (about half the size of conventional ICE powerplants) and would run at one design speed, the hybrid could be quite clean and efficient.[112] Ultimately, the ICE powerplant could be replaced by a fuel cell or gas turbine.[113]

Initially, ICE hybrids would probably run on gasoline, but by taking advantage of a proven propulsion technology such as the ICE, hybrid systems might generate early market demand for various renewable fuels and facilitate the development of an alternative fuel infrastructure. Although conventional ICEVs powered by alternative fuels could offer near-term petroleum conservation benefits, ICE hybrids perhaps offer a transitional pathway to advanced BPEVs and FCVs.

An ICE-based hybrid could run on a variety of fuels such as hydrogen, ethanol, methanol, reformulated gasoline, or natural gas. Researchers at Lawrence Livermore National Laboratory have projected the vehicle efficiencies that might be

[108]FCVs could still have a higher initial purchase price. See Delucchi, op. cit., footnote 91.

[109]An electric drivetrain is expected to result in lower maintenance costs and extend vehicle life. Ibid.

[110]See Smith, op. cit., footnote 92; and A. Burke and D. Sperling, "Hybrid Vehicles: Always Second Best?" *Future Drive: Electric Vehicles and Sustainable Transportation* (Washington, DC: Island Press, 1994).

[111]The typical urban driving cycle, with its varying speed and load demands, greatly reduces engine conversion efficiency. Some estimate that a hybrid design that would allow the ICE to operate at a single speed and load point, might double engine efficiency in comparison with current designs. See Smith, op. cit., footnote 92; and Amory B. Lovins et al., *Supercars and Nega-km: The Coming Light-Vehicle Revolution* (Snowmass, CO: Rocky Mountain Institute, Feb. 1, 1993).

[112]Note, however, that the efficiency of ICEs does decrease, all else equal, as size decreases. Also, even with a relatively small range of 40 to 50 miles, such a hybrid could meet a large fraction of the daily driving needs of many urban drivers in the electric mode (i.e., without using the heat engine). If the ICE were sized in the 25- to 40-kW range, the hybrid could travel much longer distances (i.e., the hybrid would operate in all electric mode in the city and use the ICE for highway driving). See Burke and Sperling, op. cit., footnote 110.

[113]The use of a small gas turbine as an automotive powerplant could offer a number of benefits. Gas turbines can use a number of alternative fuels, including methanol and hydrogen, and can have low emissions of criteria air pollutants. However, automotive gas turbines are still in the development stage. Reliability and efficiency are uncertain. See U.S. Department of Energy, *Conservation and Renewable Energy Technologies for Transportation* (Washington, DC: 1990); and Robert Harmon, "Alternative Vehicle Propulsion Systems," *Mechanical Engineering*, March 1992, p. 58. An upcoming OTA study will provide a detailed review of automotive gas turbines.

**TABLE 4-6: Estimates of Series Hybrid Vehicle Efficiencies[a]**

| Vehicle type | Overall vehicle efficiency for a typical urban driving cycle (percent) |
|---|---|
| Conventional Internal combustion engine vehicle (ICEV) | 12-15 |
| Battery-powered electric vehicle (BPEV)[b] | 20 |
| Gasoline internal combustion engine (ICE) hybrld[c] | 24 |
| Compressed natural gas ICE hybrid | 28 |
| Proton-exchange membrane fuel cell hybrid | *30-40* |
| Hydrogen ICE hybrld[d] | 30-40 |

[a]The comparisons are done on abasis of equal vehicle weight, drag, and rolling resistance

[b]The BPEV is assumed to be charged by a powerplant operating at 36-percent efficiency, with a power transmission efficiency Of 92 Percent The BPEV itself has an efficiency of about 50 percent, resulting in an overall efficiency of about 20 percent

[c]The electrical storage dewce is assumed 10 be an advanced flywheel having a turnaround efficiency of 95 percent

[d]It is assumed that the compression ratio for a hydrogen ICE can be raised to about 15 (conventional ICEVs have compression ratios of about 10) This would result in an engine having 48-percent efficiency

SOURCE J Ray Smith "The Hydrogen Hybrid Optlon," paper presented at the Workshop on Advanced Components for Electric and Hybrid Electric Vehicles Gaithersburg, MD, Oct 27-28, 1993

achieved using different fuels (see table 4-6). In comparison to a conventional ICEV, they estimate that a gasoline hybrid might add an additional 10 percentage points to overall vehicle efficiency for a typical urban driving schedule (24 versus 13 percent).[114] Such a vehicle would effectively double the urban mileage that could be traveled for a given quantity of gasoline. A CNG hybrid would have slightly better efficiency (28 percent), because of the higher compression ratio possible for CNG engines. Efficiencies similar to CNG would be expected when alcohol fuels are used. Perhaps most interesting, a hydrogen ICE hybrid might achieve efficiencies comparable to a fuel cell hybrid (30 to 40 percent). Thus, the hydrogen hybrid has the potential to be the "mechanical equivalent of the fuel cell." As noted before, however, these projections are subject to considerable uncertainty in terms of the efficiency of individual components and overall integrated system efficiencies. Much further research is needed to better quantify performance and to develop working demonstration vehicles for these various options.

Although tailpipe emissions from a hydrogen ICE hybrid would not be zero as from a fuel cell vehicle with onboard hydrogen, the emissions of $C0_2$, hydrocarbons, and nitrogen oxides could be significantly lower than for conventional ICEVS.[115] A hydrogen-fueled engine is potentially a near- to mid-term (10 to 15 years) technology option since prototype hydrogen ICEVs have already been developed. Because of the efficiency associated with a hybrid configuration, hydrogen storage requirements might be reduced by 50 to 65 percent compared with a hydrogen ICEV.[116] In

114 There would be essentially no improvement for highway driving, because an ICEV runs basically at one speed on the highway. ICEVs can achieve highway efficiencies of about 25 percent.

115 No ICE electric hybrid, however, has yet been built to compare emissions with pure BPEVS under real driving conditions.

116 Rambach, op. cit., footnote 60.

addition, hydrogen fuel costs over a 300-mile (480-km) operating range would not be prohibitively expensive.[117] If the difficulties associated with creating a hydrogen infrastructure can be surmounted, development of a such a hybrid might provide an important pathway to a hydrogen-based transportation systcm.

The most plausible hybrid candidates in terms of cost and technical difficulty, however, are likely to be gasoline- or alcohol-based vehicles. It should be stressed that them are serious engineering challenges confronting hybrids. For example, a hybrid vehicle will require a complex power control system that coordinates heat engine (e.g.. an ICE or gas turbine) and electrical storage system operation. In addition, much must be learned about hybrid performance, efficiency, emissions, reliability, complexity, and cost. In 1993, DOE initiated a $ 138-million, five-year program with General Motors, and a $122-million program with Ford, to design and develop prototype hybrid vehicle systems.

## POLICY ISSUES

The evolution of the U.S. transportation system toward full use of renewable energy sources in advanced vehicles could take very different directions depending on the market response and on the relative importance placed by policymakcrs on key energy and environmental issues, including urban air quality, greenhouse gas emissions, and energy security. The evolution and development of specific technologies, and of the policies that support those technologies, will be driven principally by the prospect of cost, energy security, or environmental benefits.

Although some of the propulsion technologies and alternative fuels discussed here could eventually be commercialized through the operation of normal market forces, it is not likely that such commercialization will happen in the near to mid-term, given the low prices of gasoline now available to consumers.[118] If Policymakers determine that it is necessary or desirable to introduce high-efficiency, low-emission vehicle technologies in the near to mid-term. then some level of government intervention will continue to be required.[119]

Federal policy is starting to play a major role in developing and commercializing these technologies, especially with the recent increases in federal funding for RD&D in alternative fuels and advanced vehicle technologies.

There exists abroad array of policy instruments that could affect either the supply of vehicles that use alternative fuels or the demand for them. Supply-side instruments can include increased public R&D funding and coordination, higher fuel efficiency standards, and stringent emissions regulations. Some of these options, however, do not guarantee that consumers will actually purchase vehicles that use alternative fuels. Thus, demand-side instruments might also be required. These could include lower tax rates for alternative fuels relative to gasol ine, "feebates” for energy efficien-

[117] One study estimates that a hydrogen hybrid that carried five passengers would consume about 1.5 MJ/mile (2.4 MJ/km). If the delivered cost for hydrogen ranges from $30 to $50/GJ, the fuel operating cost would range from $13 to $23 per 300 miles *(480* km). This is comparable to the operating cost of many conventional gasoline ICEVs. If advanced lightweight materials and streamlined aerodynamics were incorporated, hybrid operating costs would drop even further. Ibid.

[118] The market challenges associated with a shift to high-efficiency vehicles that use alternative fuels will be substantial. Such a shift will require extensive and expensive development of a new fuel infrastructure, retooling of portions of the automobile industry, and additional financial considerations for consumers if the new vehicles have higher upfront capital costs (even if competitive on a life-cycle basis).

[119] For example, if it is determined that national levels of greenhouse gas emissions need to be reduced below current targets, energy efficiency improvements will probably not be sufficient to achieve long-run, deep cuts in $CO_2$ emissions unless there is a switch to renewable transport fuels. Such a transition away from a petroleum-based transportation system would likely take many decades even with aggressive government intervention (see chapter 1).

BMW OF NORTH AMERICA, INC


*BMW has developed a compact electric vehicle dubbed the "E1." The concept car has been designed as an all-electric vehicle, or as an electric hybrid that uses a small ICE for long-distance travel and to recharge the vehicle's batteries.*

cy,[120] tax incentives for the purchase of advanced vehicles, pollution-based registration fees for automobiles,[121] exemptions from transportation control measures,[122] and government procurement of advanced vehicles that run on alternative fuels.

As illustrated in earlier sections, there are several plausible transition pathways that could result in greater reliance on renewable fuels. Both conventional and emerging vehicle technologies can take advantage of energy carriers such as methanol, ethanol, hydrogen, and electricity. Many economic and technical factors are, however, likely to make a transition to a renewable-based transportation system difficult.

In the short term, accelerated commercialization of ICEVs that use alternative fuels could create the groundwork for a renewable fuel infrastructure. Although many of these vehicles would bum fuels derived from nonrenewable sources (e.g., methanol from natural gas), in the near term, markets would be created that could encourage investment in renewable energy sources and technologies.

Several important policy measures for promoting the development of alternative fuels have already been taken at the federal and state levels. These are:[123]

- CAFE (Corporate Average Fuel Economy) credits are available to automakers who produce alternative fuel vehicles, permitting them to treat the vehicles as very-high-mileage cars that can be averaged into their fleets and allow fuel economy standards to be met more easily. These credits, however, are unlikely to provide much incentive to most automakers unless fuel economy standards are raised.
- The Clean Air Act Amendments (CAAA) of 1990 established three clean fuels programs: section 249 establishes a pilot test program in California; section 246 establishes a centrally fueled-fleet (10 or more vehicles) program in air quality nonattainment areas; and section 227 requires gradually increasing sales of urban buses that use clean fuels. Perhaps more

[120] Under a "feebate" system, car buyers would either receive a rebate or pay a fee based on the vehicle's fuel economy, with the fees paying for the rebates.

[121] As automobiles age, their emissions characteristics frequently deteriorate, while their registration fees Often are reduced. If registration fees were based on the emissions performance of cars, the environmental costs of driving older or underperforming cars could be partially accounted for. Such smog fees might range from $20 (for cars that use clean fuels) to $1,000 per year (for cars that emit large quantities of criteria pollutants). The fees could be used to offset the costs for low-income drivers. Some researchers believe that pollution fees could be an extremely cost-effective approach for lowering emissions. See Deborah Gordon, "Alternative Fuels Versus Gasoline: A Market Niche?" *Forum for Applied Research and Public Policy*, spring 1994, pp. 5-12; and Winston Barrington and Margaret Walls, Resources for the Future, "Shifting Gears: New Directions for Cars and Clean Air," No. 115, spring 1994, pp. 2-6.

[122] For example, consumers who purchase alternative fuel vehicles could be given permission to travel in high-occupancy-vehicle lanes. Such exemptions from transportation control measures, however, could increase congestion. See U.S. Congress, General Accounting Office, *Alternative-Fueled Vehicles: Potential Impact from Transportation Control Measures*, GAO/RCED-93-125 (Washington, DC: U.S. Government Printing Office, April 1993).

[123] The following points are drawn from and discussed more fully in Office of Technology Assessment, op. cit., footnote 14.

importantly, the CAAA requires that gasoline be oxygenated if a city is out of compliance with CO standards. As a consequence, by the turn of the century more than 70 percent of all gasoline sold could contain oxygen and thus ethanol, methanol, or their derivatives. [124] For the same mass (weight) of emissions, alternative fuels produce less ozone than gasoline because their exhaust emissions are less photochemically active. California is moving toward emissions standards that correct for this difference in the reactivity of emissions. Thus, gasoline-fueled vehicles would have to achieve lower (mass) emissions than vehicles fueled by ethanol, methanol, or their derivatives. The California Air Resources Board (CARB), however, believes that reformulated gasolines will satisfy CAAA's clean fuels requirements, which would limit the extent to which the act will actually promote alternative fuels. [125] The act Phase 11 emissions standards, set to begin in model year 2001 (if deemed necessary by EPA), are much more stringent (see table 4-3), so estimates that relatively low levels of alternative fuels will be promoted by the CAAA should be considered preliminary.

- The State of California's pilot test program under the CAAA, called the Low Emission Vehicle Program (LEVP), requires minimum sales of vehicles in different emissions categories, ranging down to zero emissions (e.g., 2 percent of vehicles sold in 1998 must be zero-emission vehicles). New York and Massachusetts have decided to adopt the California LEVP. As with the CAAA clean fuels requirements, CARB believes that reformulated gasoline, perhaps in conjunction with modified emission control systems, will satisfy most and perhaps all of the emission categories except the Zero-Emission-Vehicle (ZEV) requirement, which probably can be satisfied only with an electric vehicle or a fuel cell vehicle that uses onboard hydrogen as fuel. Some observers have criticized the ZEV requirement because it fails to consider total fuel-cycle emissions and thus might place promising technologies such as ICE-electric hybrid vehicles at a disadvantage. [126] The next most stringent category, for Ultra Low-Emission Vehicles, may generate alternative fuel use even if reformulated gasoline can satisfy its requirements, because of cost considerations. Current assessments of reformulated gasoline's ability to meet stringent emissions standards should. however, be treated cautiously.
- The Energy Policy Act (EPACT) of 1992 establishes a national goal of 10-percent alternative fuel use by 2000 and 30 percent by 2010. EPACT provides tax incentives for vehicle purchasers and for service station operations. Specific acquisition requirements are placed on federal fleets, with potential requirements for fleets run by state and local governments. Half of these nonpetroleum replacement fuels would have to be produced domestically. Thus, EPACT could encourage the development of methanol or ethanol from biomass sources. Recent analyses of the projected market penetration of alternative fuel vehicles suggest,

[124] See footnote 33.

[125] D.E. Gushee, Congressional Research Service, "Alternative Transportation Fuels: Are They Reducing 011 Imports?" CRS Issue Brief, updated Mar. 8, 1993.

[126] Depending on the assumptions, some believe that certain proposed hybrid configurations could result in zero tailpipe emissions in the city, where they would run in a pure electric mode, and have ultralow emissions on the highway. Depending on the fuel used in the ICE, the overall fuel-cycle emissions of hybrids could well be less than BPEVs when electricity powerplant emissions are taken into consideration. This might be especially true for the case of ICE hybrids that run on hydrogen. Pure BPEVs may be much cleaner on a fuel-cycle basis than gasoline ICE hybrids. No ICE-electric hybrid has yet been built to compare emissions with all-electric vehicles under real driving conditions. See Delucchi, op. cit., footnote 91.

however, that these goals will not be achieved easily.[127] Without petroleum price increases, subsidies, or tax credits to quicken the pace of product commercialization, or increased federal support of R&D activities, EPACT goals will likely not be attained in the timeframes established. Only 3 to 4 percent of the light-duty fleet in 2010 will likely be alternative fuel vehiclcs.[128]

In addition, the EPACT goals established by Congress may not be achieved unless inconsistencies with other federal policies are addressed. For example, widespread adoption of some alternative fuels such as methanol might be discouraged bccausc they are taxed at higher rates per unit of energy than gasolinc.[129] current fuel taxation policy docs not appear to take full account of the unique characteristics of alternative fuels. Fuel taxation rates seem to bear no relation to energy conservation or environmental goals. Policy makers may wish to examine the possibility of taxing each alternative fuel at the same rate in dollars per unit energy. The rate could be equal to current gasoline taxes, reflecting the government's desire to allow the market to decide, or lower to favor alternative fuels over gasoline. Consideration could also bc given to differential taxation rates that reflect each fuel's "nonrnarket" characteristics such as environmental and energy security impacts, in so far as they can be calculated, given the many uncertai nt ics.

Even if a rapid increase in alternative fuel use occurs in coming decades, markets for renewable fuels still might not emerge. It is quite possible that methanol and hydrogen, for example, would be derived from coal before biomass. This could happen if natural gas supplies become scarce before bioenergy systems are commercidized. From an environmental perspective. such a scenario would not be desirable (production of methanol and hydrogen from coal would result in relatively higher emissions of $CO_2$ in particular and possibly other air pollutants). Therefore, policy makers might want to consider how biomass fuel pathways could be specifically encouraged. One strategy, for instance, would be to intensify R&D support of enzymatic hydrolysis efforts (for the production of ethanol from woody and herbaceous crops). This could serve as an interim measure to develop a crop production and fuel transport infrastructure. Eventually, with further development of biomass gasification technology, this infrastructure could be used for the production and delivery of methanol and hydrogen. Economically competitive gasification processing would permit a greater diversity of biomass feedstocks to be exploited.

Vehicles that run on ethanol or methanol from biomass feedstocks, or on hydrogen produced from biomass or renewably generated electricity, offer the possibility of extremely clean and high-performance transportation. However, considerable R&D is necessary to bring down production costs of these alternative fuels, and in the case of hydrogen, to develop adequate storage technologies. If funding for biomass conversion programs were to be significant 1 y reduced, this would 1ikely prove to be quite damaging to biofuel commercialization efforts. Because there are a number of' challenges associated with the production and use of hydrogen as a fuel, government support is probably necessary to ensure that some types of R&D are carried out.

## Vehicle Technologies

In terms of vehicle technology, multiple R&D options exist, including R&D tax credits; direct financing of R&D through government labs,

[127] U.S. Department of Energy, Energy Information Administration, *Assumptions for the Annual Energy Outlook, 1993*, DOE/EIA-0527(93) (Washington, DC: January 1993).

[128] Ibid.

[129] D.E. Gushee and S. Lazzari, Congressional Research Service, "Disparate Impacts of Federal and State Highway Taxes on Alternative Motor Fuels," Mar. 12, 1993.

**TABLE 4-7: DOE Funding of Advanced Batteries, Electric Vehicle Systems, and Fuel Cells ($ millions)**

| | FY 1993 | FY 1994 | FY 1995 |
|---|---|---|---|
| Advanced batteries | $312 | $358 | $286 |
| Fuel cells | 119 | 193 | 230 |
| Electilc vehicle systems (prlmarlly hybrid vehicles) | 167 | 188 | 382 |
| Total | $598 | $73.9 | $899 |

SOURCE: U.S. Department of Energy, *FY 1996 Congressional Budget Request*, vol. 4, DOE/CR-0030 (Washington, DC February 1995)

university research grants, or private contracts; and joint public-private partnerships. Successful development and domestic production of high-performancc vehicles could allow the large U.S. trade imbi.dance for vehicles and parts, currently at about $45 billion per year, to be reduced.[130]

Many of the vehicle technologies receiving federal R&D support offer the promise of improved energy efficiency and environmental quality. As discussed earlier, the fuel cell vehicle is the technology that potentially offers the most benefits, but a number of serious cost and engineering barriers must bc surmounted before commercialization can occur. If system integration challenges can be met, ICE-hybrid vehicles could potentially offer a mid-term solution until FCV technologies are fully developed. Battery-powered electric vchiclcs are also an attractive option, but major breakthroughs in battery technology will probably be needed if they are to expand beyond niche markets.

Department of Energy R&D support of these technologies amounted to nearly $60 million in FY 1993.[131] Research on fuel cells, hybrids, and advanced batteries increased 25 percent in FY 1994 (see table 4-7). As part of the Partnership for a New Generation of Vehicles program,[132] total spending on fuel cell technologies for 1ight-duty vchiclcs could total more than $440 million through 2003.[133]

The strategy of pursuing several different technology options is advantageous for a variety of reasons. First, emphasizing one particular fuel-vehicl technology combination is extremely risky. There is no guarantee that any particular technology will ever satisfy the cost constraints required for large-scale cornmcrcialization. Al-

[130] U.S. Department of Commerce, International Trade Administration, *U.S. Industry Outlook 1994* (Washington, DC: U.S. Government Printing Office, January 1994), p. 35-1.

[131] In addition to DOE, the Department of Transportation (DOT) and the Advanced Research Projects Agency (ARPA) sponsored electric vehicle research. In FY 1992, DOT's appropriation was $12 million for electric vehicle R&D, while $25 million was appropriated for ARPA programs in FY 1993. In FY 1994, ARPA announced a $2.4 million program to advance the state of the art in PEM and solid oxide fuel cell technologies. ARPA funding is set up on a cost-sharing basis with the private sector.

[132] In September 1993, the White House announced the signing of an agreement between the federal government and the three domestic automakers designed to create a public-private partnership to develop a new generation of vehicles up to three times more efficient than conventional vehicles.

[133] See Mary Good, Undersecretary of Technology, U.S. Department of Commerce, testimony at hearings before the House Committee on Science, Space, and Technology, Subcommittee on Technology, Environment, and Aviation, May 19, 1994.

though more expensive in the short term, a federal R&D portfolio that explores many different technologies increases the likelihood that a low-emission, high-efficiency vehicle technology will actually be introduced to the market.[134]

Secondly, a diverse R&D portfolio can take advantage of synergies that cut across technologies. For instance, load reduction is central to all vehicle technologies; thus, reductions in aerodynamic drag or vehicle mass could be applied to ICEVs, hybrids, FCVs, or BPEVs. Advances in hydrogen storage technology could benefit corresponding FCVs, hybrid vehicles, and ICEVs. Similarly, advances in electric drivetrain technologies can be applied not only to BPEVs, but also to fuel cell and hybrid systems. Given the existence of such complementary relationships among different technologies. a multipronged R&D effort-if properly designed-can ensure that promising fuel-vehicle pathways are not abandoned prematurely. Parallel development efforts could focus on energy storage technologies (e.g., battery storage or fuel storage), electric drive technologies, and powerplant systems such as fuel cells, gas turbines, or advanced internal combustion engines. Extensive interaction between these development teams would be needed. Key elements from these modules could then be combined in prototypes for different vehicle systems. Still, some focused R&D efforts could accelerate the introduction of particularly promising technology pathways. For example, a hydrogen hybrid demonstration program could expedite the development of hydrogen engine and storage systems and thereby create momentum for the development of a hydrogen fuel distribution system.

Should there be substantial cutbacks in government R&D programs, introduction of less mature alternative vehicle technologies, such as FCVs and some types of hybrid vehicles, could be delayed. For instance, DOE now has significant cost-sharing arrangements with industry that could be affected by cutbacks in funding. Regulatory pressures and competition from foreign countries could keep up some of the momentum that has been building in the private sector for development of these technologies, but perhaps not at the same scale that exists now. For example, it is reasonable to expect that electric vehicle R&D will continue and production will increase as California ZEV requirements take effect.

## CONCLUSION

Even if economic and technical barriers can be overcome, the successful introduction of advanced automotive propulsion systems that use renewable fuels will be only a partial solution to our society's transportation problems. The issues of congestion, highway safety, and the overall efficiency of the transportation system will still need to be addressed. Settlement patterns and the role of mass transit must be considered as part of any policy strategy that seeks to modify the way in which people travel.[135] For the foreseeable future, however, the strong preference of American citizens for personal transport is unlikely to change. Thus, the evolution of vehicle technologies that utilize renewable energy sources will bean important element of the nation's effort to improve energy efficiency, reduce oil imports, and minimize disruption of the environment.

[134] This is the present strategy of the DOE Advanced Vehicle Propulsion Program. Venkateswaran and Brogan, Op. cit., footnote 3.

[135] For a detailed discussion of these issues see Office of Technology Assessment, op. cit., footnote 14.