Comparative Assessment of Fuel Cell Cars

Malcolm A. Weiss, John B. Heywood,
Andreas Schafer, & Vinod K. Natarajan

February 2003

MIT LFEE 2003-001 RP

Massachusetts Institute of Technology
Laboratory for Energy and the Environment
77 Massachusetts Avenue
Cambridge, MA 02139-4307

http://lfee.mit.edu/publications/
Publication No. LFEE 2003-001 RP

Hard copies may be ordered from:

LFEE Publications
MIT, Room E40-473
77 Massachusetts Avenue
Cambridge, MA 02139-4307

Orders must be accompanied by a check for $10.00, made payable to MIT LFEE.

Table of Contents

List of Tables

List of Figures

COMPARATIVE ASSESSMENT OF FUEL CELL CARS

Malcolm A. Weiss, John B. Heywood, Andreas Schafer, and Vinod K. Natarajan
Massachusetts Institute of Technology

Abstract

This study extends our previous work on the assessment of new propulsion technologies as potential power sources for light duty vehicles that could be commercialized by 2020. The focus is, as previously, on technologies with lower energy consumption and lower greenhouse gas (GHG) emissions over the life cycle which includes not only operation of the vehicle on the road but also the manufacture and distribution of both the vehicle and the fuel, during the vehicle's entire lifetime. In this extended work, our purpose was to determine how competitive fuel cell (FC) vehicles would be with internal combustion engine (ICE) vehicles if advances in FC technology were closer than previously assumed to the higher targets foreseen by some FC advocates.

The methodologies used to carry out these assessments were the same as used previously. We considered future (about 20 years) ICE systems fueled by gasoline and diesel fuel, and FC systems fueled by compressed hydrogen made from natural gas and by gasoline converted on board to hydrogen. The results show that, considering the uncertainty of long-range predictions and judging solely by lowest life-cycle energy use and GHG releases, there is no current basis for preferring either FC or ICE hybrid power plants for mid-size automobiles over the next 20 years or so. That conclusion applied even with optimistic assumptions about the pace of future fuel cell development. Hybrid vehicles are superior to their non-hybrid counterparts and their advantages are greater for ICE than for FC designs. Hybrids can reduce both life-cycle energy use and GHG emissions to about 37 to 47% of current comparable vehicles and to about 52 to 65% of what might be expected in 2020 as a result of normal evolution of conventional technology. For both hybrids and non-hybrids, and for both ICE and FC vehicles, the reductions in energy use and GHG releases result from not only advances in power plants and powertrains, but also from reduction of both vehicle weight and driving resistances such as aerodynamic drag and tire rolling resistance.

However, FC and ICE vehicles will differ in other important respects. FC vehicles will be quieter and will have lower non-GHG tailpipe emissions, but will be more expensive and will require new infrastructures for vehicle manufacturing and maintenance and for producing and distributing hydrogen fuel—thus making rapid acceptance and market penetration more difficult. There are large uncertainties about how all these technologies will develop, especially fuel cells, and especially over longer time horizons. All our assessments are therefore uncertain. Important uncertainties are not confined to energy and GHG results. They extend to cost, to diesel ICE tailpipe emissions, to other performance attributes of FC vehicles, and to customer acceptance. If automobile systems with GHG emissions much lower than the lowest here are required in the very long run future (perhaps in 30 to 50 years or more), hydrogen is the only major fuel option identified to date, but only if the hydrogen is produced from non-fossil sources of primary energy (such as nuclear or solar or biomass) or from fossil primary energy with carbon sequestration.

Introduction

Automotive manufacturers and suppliers around the world are investing heavily in the development of fuel cell systems (FCSs) as potential power sources for light duty vehicles. In our previous assessment of new automobile technologies that could be commercialized by 2020 [1], [2], future FCSs showed no advantage over future internal combustion engine (ICE) systems with respect to life-cycle greenhouse gas (GHG) emissions, energy efficiency, or cost when the hydrogen used to power the FCSs originated from a hydrocarbon raw material such as natural gas or gasoline.

As in all comparisons of future alternatives, the results depended on the particular assumptions made about each alternative and are subject to large uncertainties inherent in looking ahead for many years. In the study reported here, we used the same methodologies used in [1] but we have made more optimistic assumptions about the performance of future FCSs. Our purpose was to determine how competitive FCSs would be in comparison with ICESs assuming advances in FCS technology closer to the higher targets foreseen by some FCS advocates. The study does not make predictions about which technologies will be developed nor judgments about which technologies should be developed—issues for the marketplace and for public policy that are not examined here.

Scope

The primary motivation for the assessments reported both here and previously was to evaluate new automobile technologies which might function with lower emissions of GHGs, generally believed to contribute to global warming. The GHG of most concern is carbon dioxide (CO_2) which is contained in the exhaust gases of vehicles burning petroleum or other carbon-containing fuels. If public policy or market forces result in constraints on GHG emissions, automobiles and other light-duty vehicles—a key part of the transportation sector—will be candidates for those constraints since the transportation sector accounts for about 30% of all CO_2 emissions in OECD countries, and about 20% worldwide. Therefore, new low-GHG emitting technologies are of broad interest.

To validly assess and compare emissions from future vehicle technologies, the methodology must consider the total system over its entire life cycle. The life cycle of an automotive technology is defined here to include all the steps required to provide the fuel, to manufacture the vehicle, and to operate and maintain the vehicle throughout its lifetime up to and including scrappage and recycling. An example of why life-cycle assessment is essential is the case of an automobile using a new fuel that permits the automobile to consume less fuel and emit less CO_2 per kilometer traveled while on the road. But there may be no net benefit if more energy and more CO_2 emissions are required to provide that new fuel (instead of the established fuel) before the fuel ever gets into the automobile tank.

Provision of the fuel from primary energy sources such as petroleum or natural gas must be considered from the point of resource recovery from underground reservoirs through transportation to refineries or manufacturing plants where those resources are converted to fuels for vehicles. The fuel must then be distributed and deposited in the vehicle's tank. The total of these steps is often called "well-to-tank". Analogously, the vehicle manufacture begins with ores or other raw and recycled materials necessary to make the parts included in a vehicle, fabrication and assembly of those parts, and distribution of the finished vehicle to the customer. The vehicle is then operated by the first or subsequent customer, with maintenance and repair requirements, until the end of its lifetime when the vehicle is scrapped and recycled. Vehicle operation is often called "tank-to-wheels". "Well-to-wheels" ordinarily means "well-to tank" plus "tank-to-wheels" but does not ordinarily include vehicle manufacture which should be included in a comprehensive life cycle analysis.

The new results reported here are confined to the "tank-to-wheels" part of the life cycle. However, we combine those new results with earlier results on "well-to-tank" and vehicle manufacturing to make new comparisons on a total life cycle basis.

Vehicle and Driving Parameters

All the vehicles examined in this study are designed to be functional equivalents of today's typical US mid-size family sedan. For the customer, this means that characteristics such as acceleration, range, passenger and trunk space are maintained in future vehicles. All vehicles are designed to have the same ratio of peak power to vehicle mass, namely 75 W/kg, which is approximately today's average value and roughly equalizes the short-time acceleration performance of all vehicles; exactly equalizing all aspects of vehicle performance would require more complex analysis beyond the scope of our study. The methodologies used for assessing and comparing technologies are described in detail in [1] and are not repeated here.

The propulsion systems reported here consist of a) advanced spark and compression ignition ICEs, fueled by gasoline and diesel fuel respectively, in both parallel hybrid and non-hybrid configurations, and b) fuel cell systems fueled by compressed 100% hydrogen or by hydrogen (about 40% by volume) in gas generated by processing gasoline on board, also in both hybrid and non-hybrid configurations. The systems are listed in Table 1.

For all hybrid systems the battery and electric motor were sized to provide a ratio of peak electrical power to vehicle mass of 25W/kg, and the power plant (ICE or FC) to provide 50 W/kg, giving the total of 75 W/kg cited above. All hybrid systems included regenerative braking. Although these hybrids provide short-time vehicle acceleration comparable to non-hybrids, they have inferior performance at higher speeds while climbing long hills or towing heavy loads. We did not attempt to optimize hybrid designs by assessing options such as varying the relative battery and engine sizes. Choosing "optimum" designs would depend on selecting from particular characteristics of cost, fuel economy, and performance those characteristics to be given priority.

All vehicles, except the 2001 reference and the 2020 "evolutionary base case", used the same type of advanced body with changes designed to reduce vehicle mass (e.g. more extensive use of aluminum) and resistances (e.g. lower drag coefficient and rolling resistance). See [1] for details. Both propulsion system and body features consist of changes we believe could be commercialized broadly by 2020 if pursued aggressively—with some qualifications about fuel cell system performance discussed further below.

These vehicles are compared to the typical current US mid-size family sedan, for "reference", and to a 2020 evolutionary "baseline". Both the reference and the baseline are gasoline-fueled ICE cars with similar capacity and performance; the baseline has evolutionary improvements in fuel and vehicle over the next 20 years or so similar to improvements achieved during the last 20 years.

The relative fuel economy of different propulsion systems can be expected to change with changes in the power demand on the system, a function of the way the vehicle is driven. Therefore, we have examined the economy of each system following each of the three different driving cycles described in Table 2.

The performance of each of the vehicles we assessed was calculated using computer simulations described in [1]. Originally developed by Guzzella and Amstutz [3] at the Eidgenossiche Technische Hochschule (ETH), Zurich, these simulations back-calculate the fuel consumed by the propulsion system by driving the vehicle through a specified cycle. Such simulations require performance models for each major propulsion system component as well as for each vehicle driving resistance. The simulations we used, which are updated and expanded versions of the Guzzella and Amstutz simulations, are best characterized as aggregate engineering models which quantify component performance in sufficient detail to be reasonably accurate but avoid excessive detail which would be difficult to justify for predictions relevant to 2020.

Fuel Cell System Performance

Since the emphasis in this study is on the comparative energy consumption of advanced fuel cell vehicles, our assumptions about the performance of fuel cell systems (FCS) are reported in some detail below. We define the FCS here to include a fuel processor (for gasoline fuel) which converts the fuel chemically to hydrogen, hydrogen cleanup equipment, a "stack" which converts hydrogen electrochemically to electric power, associated equipment for heat, air, and water management, and auxiliary equipment such as pumps, blowers, and controls. Fuel tanks are excluded as is all equipment downstream of the stack's net electrical DC output.

The overall efficiency of an FCS is defined here as the net DC energy output of the stack (after subtracting from the gross output the electrical energy needed to operate FCS auxiliaries such as pumps and compressors) divided by the lower heating value (LHV) of the fuel consumed in the FCS—whether gasoline fed to a fuel processor or hydrogen gas from a high pressure tank or other on-board hydrogen storage device. That overall efficiency will vary with the load on the fuel cell and will generally increase as load decreases except at very low loads when parasitic power losses and/or fuel processor heat losses become comparatively high and overall efficiency declines.

We assume that all these FCSs include proton exchange membrane (PEM) stacks in which hydrogen, pure or dilute, at the anode side of the electrolyte—a plastic membrane such as a perfluorinated and sulfonated polymer—reacts with oxygen in air at the cathode side of the electrolyte to produce water and electric power. The anode and cathode are porous electrodes impregnated with catalytic metals, mostly platinum. We assume the stacks operate at about 80ºC and a maximum pressure (at peak power) of about 3 atmospheres.

The main loss of efficiency in the FCS fueled by pure hydrogen occurs in the stack itself where some of the fuel energy consumed is converted to heat—through resistance losses and other types of "polarization" losses—rather than to electrical energy. The secondary loss in these FCSs is consumption of electrical energy to drive motors essential to the FCS itself, for compressing air and for pumping water, for example.

FCSs fueled by dilute hydrogen from gasoline reformate have the same two types of losses in efficiency that pure-hydrogen FCSs suffer, but also have two additional types: 1) losses in the "fuel processor" during conversion of gasoline (by reaction with steam and air) to hydrogen, and subsequent cleanup of that hydrogen to remove stack catalyst poisons, and 2) incomplete hydrogen utilization, namely losses of unreacted hydrogen in "tail gas" from the stack where the hydrogen becomes so dilute that it must be purged but can be used to supply energy to the fuel processor or to the air compressor-expander. We assume a hydrogen utilization of 85% as we did in [1]. That is, 15% of the hydrogen entering the stack from the fuel processor is purged and thus leaves the stack unreacted.

The key objectives for advanced FCSs for vehicles are improved overall efficiency, as a result of reducing some or all of the losses described above, and reduced cost and weight per unit of net electrical power output.

Characteristics of Advanced Fuel Cell Systems

We estimated the extent to which advanced technology might reduce FCS losses by reviewing recent fuel cell literature and by discussing the outlook for commercialization before 2020 with FCS analysts and with commercial component and vehicle developers. Our objective was to identify and assume advances in FCS technology that were plausible—but not assured—with aggressive development, but to not assume advances that depended on hoped-for technical innovation not yet demonstrated at least in bench experiments. We included only advances whose cost looked at least plausible commercially. For example, stack polarization losses could be reduced even more than we assumed—but at increased cost—by increasing concentration of platinum catalysts or by increasing stack area for a given power output, or by both.

Specifically, the new stack polarization data we chose corresponded to the current Ballard Mark 900 80 kW stack [4] with unit cell voltage increased by 0.05 V (about 5 to 8%) at all current densities to anticipate further improvements. We also assumed that operating a stack of given area on gasoline reformate rather than pure hydrogen would reduce peak power density and cell voltage by amounts consistent with the Ballard Mark 900 experience and with other previous data [5]. Table 3 lists the polarization data used in this report. For our stack conditions, the ideal unit cell voltage is 1.22-1.23 V; the ideal voltage excludes all the losses found in an operating fuel cell.

For this study we define peak power as the power level at which unit cell voltage drops to 0.6V for both pure hydrogen and reformate fuels. Although somewhat more power could be produced by the stack by drawing more current and allowing the unit cell voltage to drop below 0.6V, heat removal problems increase and 0.6V is probably close to the minimum voltage for optimizing the total system. Heat released in the stack is equal to the higher heating value of the hydrogen consumed minus the gross electrical energy produced.

At all current densities, the voltages assumed are significantly (as much as 40%) higher than the voltages assumed in [1] which were the voltages reported by Thomas [6] and which represented published data in 1998. The consequences of this change for overall system efficiency are discussed further below. In the stacks considered in this report, the pure hydrogen stack at gross peak power operated at a unit cell voltage of 0.60 V, a current density of 1300 mA/cm^2, and a power density of 780 mW/cm^2 while the reformate stack, at peak, operated at 0.60 V, 1050 mA/cm^2, and 630 mW/cm^2.

For FCSs fueled by processing gasoline to hydrogen, a customary expression of efficiency of the processor (including removal of CO from the gas stream) is equal to the LHV of the hydrogen in the gas stream leaving the processor divided by the LHV of the gasoline fed to the processor. This efficiency is often increased by supplying heat to the fuel processor by burning the hydrogen in the tail gas purged from the stack, referred to previously.

The efficiency of the FCS declines at low power output because heat losses from the fuel processor became a significant fraction of the heat required for the reaction to make hydrogen. Published data for performance at low outputs are sparse and probably are sensitive to the specifics of processor and heat exchanger design; the numbers assumed therefore are particularly uncertain.

Table 4 lists the efficiencies assumed in this study for gasoline fuel processors feeding a stack whose peak power output is about 60 kW. At high power, the efficiency is 0.81 LHV compared to 0.725 LHV assumed in our previous study. US DOE's current 2001 "baseline" (at peak power) is 0.76 [7]. Some reformers under development are claimed to have higher efficiencies but, according to a Ford authority quoted by DeCicco [8], "Effective reformers exist only in the laboratory".

A third source of loss in FCSs is the energy needed for FCS auxiliaries, primarily electrically-driven pumps and blowers for water, air, and heat management. The single largest load is for an air compressor to deliver air to the cathode compartments of the stack; some of the air compressor load can be offset by an expander powered by the cathode exhaust gas. In FCSs fueled by gasoline reformate, the air compressor must also deliver air to the fuel processor for reaction with gasoline and recycled purged hydrogen to provide reforming heat.

Table 5 shows our assumptions about total net requirements (after taking credit for the expander) for auxiliary power expressed as a fraction of stack gross power. As in the case of fuel processors, data are sparse at low levels of stack power output, and future estimates are disparate, e.g. [8]. There are uncertainties about potential advances in compressor/expander technologies, in optimum tradeoffs between cost and efficiency, and in optimum pressures for the stack system.

In addition to these new assumptions, we made some minor adjustments to the model in [1] and corrected a significant error we found in the computer code for the simulation of gasoline and methanol fuel cell hybrid systems. That is, the heating value of hydrogen from the fuel processor was not converted from the LHV to the HHV as it should have been to correctly calculate the consumption of gasoline and methanol; that error resulted in estimates of fuel consumption for the gasoline and methanol FCS vehicles that were about 15% too high.

Unit Cost and Weight

In addition to projecting greater future advances in FCS efficiency, we considered the prospects for greater reduction of both FCS cost and weight per peak kilowatt of electrical power available from the FCS.

Many projections of FCS costs reflect targets rather than an analysis of specific design and manufacturing steps that would directly determine FCS costs. That is, targets are the costs that would have to be achieved to be competitive with ICE systems. An example is the FreedomCAR target [9] of $30/kW by 2015 (Table 6) for FCS systems fueled by hydrogen (including fuel tank) or by gasoline. (In [1] we used $70/kW for the hydrogen-fueled FCS including tank, and $80/kW for the gasoline-fueled FCS.)

For comparison, the ADL analysis [7] estimates high volume manufacturing costs in 2001 for gasoline FCS to be $324/kW although a reduction to $259/kW could be achieved by reducing FCS efficiency by 20%. A pertinent statement in ADL's report was "Our discussions with component and system developers did not find pathways to significant cost reductions."

However, in another study [10], ADL did estimate potential costs of future FCS using results from analyses done with DOE and EPRI. Even with optimistic assumptions about future FCS performance and costs, ADL concluded that "factory costs of future FCVs would likely be 40-60% higher than conventional vehicles". Typical annual ownership costs for fuel cell vehicles would therefore be about $1200 to $1800 higher than for ICE vehicles. For all vehicles, depreciation accounts for "over 75% of annual cost"; the higher factory costs of FCVs means higher depreciation costs and thus higher annual costs. Long-term factory costs for the FCS were estimated at about $105/kW for hydrogen and about $130/kW for gasoline fuel processor systems.

Accordingly, we have not re-estimated vehicle costs since the costs reported in [1] already seem to be optimistic. Those costs were $18,000 for our 2020 baseline vehicle, 8 and 14% higher for advanced gasoline and diesel vehicles respectively, 17 and 23% higher for gasoline and diesel hybrids, and 23 and 30% higher for hydrogen and gasoline fuel cell hybrids. Our assumptions about fuel costs also remain the same since no new technologies have been identified likely to make a major change in the costs of the fuels we considered. ADL [11] notes that our fuel costs and fuel-chain energy use and GHG emissions were comparable to other studies.

Our previous projections for FCS unit weights still look optimistic but achievable and we have not changed them. For example, our estimate of 2.9 kg/kW for the hydrogen-fueled FCS compares to the 3.1 target for the FreedomCAR [9]. Our estimate of 4.8 kg/kW for gasoline FCS compares to ADL's [7] estimate of about 11 for 2001 technology and their long-term projection of 3.5 for systems based on an extremely efficient stack which reduces weight not only in the stack but throughout the FCSs.

Overall System Efficiency

The losses enumerated above can be combined to give overall FCS system efficiencies. Losses (and regenerative gains) downstream of the stack, in the electrical traction system and controls, are excluded.

Overall efficiencies are listed in Table 7 under the heading "Components". We use the term "components" because the numbers shown combine the efficiencies (or losses) of the individual FCS components listed in Tables 3 to 5 with no allowance for performance degradation of those components due to design compromises needed to obtain the best combination of important characteristics of the total powerplant in the vehicle.

Examples of such compromises—often to reduce cost, weight, or space or to provide for warmup or transients—would be lower stack efficiency due to smaller stack area, lower processor efficiency due to simpler but less-effective processor heat management, or lower hydrogen utilization through changed stack design and operation. Lacking any specific way to estimate these losses in a total integrated system, we simply assumed an increase of 5% in the losses in each component. That is, the column "Integrated" in Table 7 shows overall FCS efficiencies based on the component efficiencies assumed in the "Components" column but additionally assuming: a) in the stack, unit cell voltage is reduced 5% (from, say, 0.8 V to 0.76 V) at any given power density, b) auxiliary power requirements are increased 5% (from, say, 10% of net output to 10.5%) at any given power, and c) all efficiencies in the reformer are decreased 5% (from, say, an efficiency of 0.80 to 0.76). We did not change hydrogen utilization; it remained at 85%. These assumed losses due to integration result in significant increases in fuel consumption relative to the "component" losses for the fuel cell vehicles evaluated. Consumption of on-board fuel per vehicle km traveled increases about 9 to 23% depending on the driving cycle, fuel, and hybridization.

On-the-Road Results

Table 8 lists the assumed characteristics and the on-the-road and life-cycle energy consumptions and GHG emissions of all the ICE vehicles we assessed. Table 9 does the same for all the FC vehicles.

Some of the results from Tables 8 and 9 are displayed in Figure 1 for the combined 55% urban/45% highway US Federal Test Procedure driving cycles. All of the tank-to-wheels fuel consumptions are compared on a relative scale where 100 is defined as the consumption of an assumed "baseline" car—a gasoline-engine non-hybrid car—with low-cost evolutionary improvements in engine, transmission, weight, and drag assumed to take place by 2020. The projected on-board fuel consumption of the baseline car in the 55/45 driving cycle is 5.4 l gasoline/100 km which is equivalent to 43 miles per gallon or 1.75 MJ (LHV)/km. The 2001 predecessor[*] of the baseline car had a fuel consumption of 7.7 l/100 km (30.6 mpg) or 2.48 MJ (LHV)/km.

The bar for each of the fuel cell vehicles in Figures 1-3 has a shaded area and a hatched area. The shaded area indicates the fuel consumption based on assuming that each of the components of the FCS can operate as efficiently as shown in Tables 3 to 5 with an overall FCS efficiency shown in the "Components" columns of Table 7. The hatched area shows the additional fuel consumption due to efficiency losses through integration as summarized in the "Integrated" columns of Table 7.

In comparing different vehicles, modest differences are not meaningful because of uncertainties in the results. We have not tried to quantify those uncertainties but some sense of their magnitude can be gotten from two recent studies [12] [13] by General Motors on ICE and FCS engines with hybrid and non-hybrid powertrains in a full-size pickup truck and an Opel minivan using "technologies that are expected to be implemented" or "can be made technically available". GM projected median consumptions of on-board fuel, with consumption equally likely to be above or below the median. They also reported uncertainties defined as 20% bounds—levels of fuel consumption such that consumption has a 20% likelihood of being higher than the higher bound and a 20% likelihood of being lower than the lower bound. These "20% bounds" varied with technology, but were about 20% above and below the median fuel consumption.

Life-Cycle Results

In order to estimate life-cycle energy consumption, additions of energy use for the fuel and vehicle manufacturing cycles were made to the tank-to-wheels estimates as shown in the last rows of Tables 8 and 9. Estimates of life-cycle GHG emissions were made similarly. For GHG emissions, the only GHGs considered were CO_2 and methane from natural gas leakage; gC(eq) is equal to the carbon in the CO_2 released plus the carbon in a mass of CO_2 equal to 21 times the mass of methane leaked.

During the fuel cycle, gasoline and diesel fuels were assumed to be refined from crude petroleum and would have modest improvements in quality over the next 20 years. Hydrogen was assumed to be produced by the reforming of natural gas at local filling stations, and compressed to about 350 atmospheres for charging vehicle tanks. Energy consumptions during the manufacturing and distribution of these fuels were calculated to include energy from all sources required to produce and deliver the fuels to vehicle tanks. GHG emissions were calculated similarly. Details can be found in [1]. For each MJ(LHV) of energy delivered to the vehicle fuel tank, energy consumption and GHG emissions during the fuel cycle were 0.211 MJ and 4.9 gC(eq) respectively for gasoline, 0.139 MJ and 3.3 gC(eq) respectively for diesel fuel, and 0.77 MJ and 36 gC(eq) respectively for hydrogen.

---

[*] This "2001 predecessor" differs somewhat from the "current vehicle (1996) predecessor" cited in [1], reflecting advances in current technology during the past several years.

For vehicle "manufacturing" (which also includes all materials, assembly, and distribution), we assumed, as in our previous report [1], intensive use of recycled materials (95% of all metals and 50% of glass and plastics) in manufacturing, and that manufacturing energy and GHGs were prorated over 300,000 km (vehicle life of 15 years driven 20,000 km/year). These manufacturing additions for the vehicles assessed ranged from 0.25 to 0.33 MJ/km in energy consumed and about 4.8 to 6.3 gC(eq)/km of GHGs released. The numbers are the numbers used in [1] for the same vehicle technologies but with small adjustments for changes in vehicle mass.

The life-cycle results are shown for energy in Figure 2 and for GHGs in Figure 3. On a life-cycle basis, both energy consumption and GHG releases are similar for two hybrid vehicles: diesel ICE and hydrogen FC. The gasoline ICE and FC hybrids appear to be not quite as efficient but, considering the uncertainties of the results, not significantly different from the two other hybrids.

Both life-cycle energy use and GHG releases from all four of these hybrids are between 52 and 65% of our 2020 baseline vehicle, and between 37 and 47% of our 2001 reference vehicle. Whether or not fuel cell vehicles can reach the levels of performance assumed here, there are several different technical opportunities to develop light-duty vehicles capable of major reductions in energy and GHGs from personal passenger transportation.

Table 10 breaks down life-cycle energy and GHG totals into the shares attributable to each of the three phases of the life cycle: operation of the vehicle on the road, production and distribution of fuel, and manufacture of the vehicle including embodied materials.

The largest single share of energy, ranging from 44 to 75% of the total, results from vehicle operation. The largest single share of GHGs, from 65 to 74%, is also attributable to operation except for hydrogen fuel where the fuel cycle accounts for about 80% of the total. Vehicle manufacturing increases its share of energy and GHGs for vehicles with higher on-the-road fuel economies, up to about 21% and exceeding the fuel cycle share in about half the 2020 vehicles.

The main driving force for hybrid vehicles is their greater fuel economy which comes at the cost of higher initial price and complexity, and some performance disadvantages noted previously. The extent of the advantage in fuel economy depends importantly on the way in which the vehicle is driven with greatest hybrid advantages for urban driving and smaller advantages for higher speed highway and US06 driving. The differences are illustrated by Table 11 which lists each hybrid's fuel consumption as a percentage of the fuel consumption of the corresponding non-hybrid version for the US06, urban, highway, and combined Federal driving cycles. As expected, hybrids also improve the urban fuel economy of ICE vehicles, whose engines have lower efficiencies at lower power (and speeds), more than they improve FC vehicles whose fuel cell stacks have higher efficiencies at lower power.

Comparison with Earlier Results

The on-board energy consumptions of the vehicles covered in this report can be compared with those of our earlier report [1]. The comparisons below are based on MJ(LHV)/km of the vehicles operated over the combined Federal driving cycles (weighted as 55% urban and 45% highway). Results are summarized in Table 12.

The adjustments and corrections we made to our earlier simulations and assumptions resulted in no change in energy consumption for any gasoline ICE vehicles, a reduction of less than 4% in consumption for the diesel ICE vehicle, and less than 1% for the diesel ICE hybrid vehicle. The diesel improvements resulted largely from increasing the brake mean effective pressure in the turbocharged diesel engine by an additional 10% at all engine speeds, reflecting progress in diesel development, and thus also permitting a small reduction in engine mass since engine power-to-weight ratio rose from 0.60 to 0.64 kW/kg

As intended, the adjustments for fuel cell vehicles resulted in much better performance than we reported previously for similar vehicles in [1].

On-board fuel consumption in hydrogen fuel cell hybrid vehicles was reduced 33% for component FC systems and 27% after allowing for losses in integrated total systems. On-board fuel consumption in gasoline fuel cell hybrid vehicles was reduced 43% for component systems and 32% for integrated total systems after correcting for the original computer code error in heating value noted previously. Gasoline fuel cell hybrids are now comparable to other hybrids on a life-cycle basis after making that correction and our new assumptions. For all FC vehicles, the reduction in fuel consumption is accounted for largely by the assumed improvements in stack performance. Remaining reductions resulted from lower losses for powering auxiliaries and, for gasoline, in higher efficiency of the fuel processor.

Conclusions

Considering the uncertainties of long-range predictions and judging solely by lowest life-cycle energy use and greenhouse gas (GHG) releases, there is no current basis for preferring either fuel cell (FC) or internal combustion engine (ICE) hybrid powerplants for mid-size automobiles over the next 20 years or so using fuels derived from petroleum or natural gas. That conclusion applies even with optimistic assumptions about the pace of future fuel cell development. Hybrid vehicles are superior to their non-hybrid counterparts and their advantages are greater for ICE than for FC designs.

Hybrids can reduce both life-cycle energy use and GHGs to about 37 to 47% of current comparable vehicles, and to about 52 to 65% of what might be expected in 2020 as a result of normal evolution of conventional technology. For both hybrids and non-hybrids, and for both ICE and FC vehicles, the reductions in energy use and GHG releases result from not only advances in power plants and powertrains but also from reduction of both vehicle weight and the driving resistances of aerodynamic drag and tire rolling resistance.

However, FC and ICE vehicles will differ in other important respects. FC vehicles will be quieter and will have lower non-GHG tailpipe emissions, but will be more expensive[*] and will require new infrastructures for vehicle manufacturing and maintenance and for producing and distributing hydrogen fuel—thus making rapid acceptance and market penetration more difficult. Therefore, if it is important to make significant reductions in fleet energy use and GHG emissions during the next 20 years, then improved ICE vehicles offer the quickest and easiest technology options for realizing those objectives.

There are large uncertainties about how all these technologies will develop, especially fuel cells, and especially over longer time horizons. Therefore, all our assessments are correspondingly uncertain. Important uncertainties are not confined to energy and GHG results. They extend to cost, to diesel ICE tailpipe emissions, to other performance attributes of FC vehicles, and to customer acceptance. Successful development and penetration of new technologies requires acceptance by all major stakeholder groups: private-sector fuel and vehicle suppliers, government bodies at many levels, and ultimate customers for the products and services. Therefore, the economic, environmental, and other characteristics of each technology must be assessed for their potential impacts on each of the stakeholder groups.

If automobile systems with GHG emissions much lower than the lowest estimated here are required in the very long run future (perhaps in 30 to 50 years or more), hydrogen is the only promising fuel option identified to date--but only if the hydrogen is produced from non-fossil sources of primary energy (such as nuclear or solar) or from fossil primary energy with carbon sequestration. Biofuels may increase their currently limited role. In principle, a battery-electric car run on non-fossil electric power would also almost eliminate life-cycle GHG emissions, but the prospects are not promising for batteries good enough to make battery cars competitive with other types of cars in range and performance.

A comparison of the on-the-road and life-cycle energy and GHG results for hydrogen—superior in the former but about the same in the latter—illustrates why a valid comparison of future technologies for passenger cars must be based on life-cycle analysis for the total system, which includes assessment of fuel and vehicle manufacture and distribution in addition to assessment of vehicle performance on the road.

---

[*] The engineer in charge of fuel cells for Honda, a company that is now leasing hydrogen fuel cell cars in the US, says that it will take at least 10 years to bring prices down to $100,000 [14].

References

1. Weiss, Malcolm A., et al. "On the Road in 2020: A life-cycle analysis of new automobile technologies". Energy Laboratory Report # MIT EL 00-003, Massachusetts Institute of Technology, October 2000. http://web.mit.edu/energylab/www

2. AuYeung, F., et al. "Future Light-Duty Vehicles: Predicting their Fuel Consumption and Carbon-Reduction Potential". Massachusetts Institute of Technology. SAE 2001-01-1081.

3. Guzzella, L., and A. Amstutz. "Quasi-Stationaren-Simulations". Matlab programs and text Benutzeranleitung, Laboratorium fur Motorsysteme, Institute fur Energietechnik, ETH-Zurich, 1998.

4. Ballard Power Systems. "Ballard Fuel Cell Power Module, Mark 900 Series, Mk 900 Polarization". Burnaby, BC, Canada, November 2001.

5. Barbir, Frano, et al. "Design and Operational Characteristics of Automotive PEM Fuel Cell Stacks". Energy Partners, LC, West Palm Beach, FL. SAE 2000-01-0011.

6. Thomas, D. E., et al. "Societal Impacts of Fuel Options for Fuel Cell Vehicles". Directed Technologies, Inc. SAE 982496. Presented at Society of Automotive Engineers International Fall Fuels and Lubricants Meeting and Exposition, San Francisco, California, October 19-22, 1998.

7. Arthur D. Little, Inc. "Cost Analysis of Fuel Cell System for Transportation, 2001 System Cost Estimate, Task 3 Report to: Department of Energy", Ref. 49739 SFAA No. DE-SCO2-98EE50526, August 2001.

8. DeCicco, John M. "Fuel Cell Vehicles: Technology, Market, and Policy Issues". SAE Research Report RR-010, November 2001.

9. US Department of Energy. "FreedomCAR Goals". Office of Advanced Automotive Technologies. http://www.cartech.doe.gov/freedomcar/technical-goals.html

10. Arthur D. Little, Inc. "Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles, Main Report, Phase II Final Report to DOE", 35340-00, December 14, 2001.

11. Arthur D. Little, Inc. "Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles, ADL Phase II Results Comparison to MIT Study, Revised Phase 3 Deliverable to DOE", 75111-00, February 26, 2002.

12. General Motors Corporation, et al. "Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems—North American Analysis". Volume 2. http://www.transportation.anl.gov, June 2001.

13. L-B-Systemtechnik GmbH. "GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems—A European Study." Report plus annexes: http://www.lbst.de/gm-wtw , 27 September 2002.

14. *Business Week*, "Fuel Cells: Japan's Carmakers are Flooring It", p. 50, December 23, 2002.

Table 1. Propulsion Systems Assessed

Propulsion System	Description
Gasoline ICE	Advanced SI engine and auto-clutch transmission
Gasoline ICE hybrid	Gasoline ICE powertrain with CV transmission plus battery and electric motor running in parallel
Diesel ICE	Advanced CI engine and auto-clutch transmission
Diesel ICE hybrid	Diesel ICE powertrain with CV transmission plus battery and electric motor running in parallel
Hydrogen FC	Fuel cell operating on 100% compressed hydrogen with electric drive train
Hydrogen FC hybrid	Hydrogen FC with addition of a battery
Gasoline FC	Like the Hydrogen FC, but fueled by hydrogen produced by processing gasoline on board
Gasoline FC hybrid	Gasoline FC with addition of a battery

Table 2. Driving Cycles

Driving Cycle	Description
Urban	The US FTP 75 cycle, which describes city driving
Highway	The US HWFET cycle, which describes highway driving
US06	The US06 cycle which exhibits aggressive speed and acceleration
“Combined”	Fuel consumption calculated for 55% of total as urban driving and 45% as highway

Table 3. Stack Polarization Data

Current Density ma/cm^2	Unit Cell Voltage, V	
	100% H_2	40% H_2 (reformate)
0	1.05	1.03
25	0.94	0.92
50	0.90	0.88
100	0.87	0.84
200	0.84	0.81
400	0.79	0.75
600	0.75	0.71
800	0.72	0.67
1000	0.68	0.61
1050	--	0.60
1200	0.63	--
1300	0.60	--

Table 4. Efficiencies of Gasoline Fuel Processors

Stack Gross Power, % of Peak	Efficiency $LHV_{H2\ Out}/LHV_{Gasoline\ In}$	
	Previous Study [1]	This Study
0	0.725	0.60
5	0.725	0.73
10	0.725	0.79
20	0.725	0.81
30	0.725	0.81
100 (Peak)	0.725	0.81

Table 5. FCS Auxiliary Power Requirements

Stack Gross Power, % of Peak	Auxiliary Power as Percent of Gross Stack Power	
	Previous Study [1]	This Study
5	15	15
10	15	12
20	15	10
30	15	10
100 (Peak)	15	10

Table 6. Unit Cost and Weight of Future Fuel Cell Systems
Ex fuel and storage

Source [Reference]	100% Hydrogen Fuel		Gasoline Reformate	
	$/kW	kg/kW	$kW	kg/kW
Previous Study [1]	60	2.9	80	4.8
DOE [7]	28	1.8	45	3
FreedomCAR [9]	30*	3.1*	30	--
ADL [11]	105	--	130	3.5

* Includes hydrogen storage

Table 7. Overall Fuel Cell System Efficiencies

Net Output Energy, % of Peak	100 x Net DC Output Energy/Fuel LHV			
	100% Hydrogen Fuel		Gasoline Reformate Fuel	
	Components	Integrated	Components	Integrated
5	76	71	46	42
10	75	71	50	45
20	74	70	49	44
40	69	65	46	42
60	65	61	44	39
80	61	58	41	37
100	53	50	36	33

Table 8. Vehicles Using Internal Combustion Engines

	Gasoline				Diesel	
	2001	**2020**	**2020**	**2020**	**2020**	**2020**
	Reference	**Baseline**	**Advanced**	**Hybrid**	**Advanced**	**Hybrid**
Mass (kg)						
Body & Chassis	930	845	746	750	757	758
Propulsion System (3)	392	264	252	269	293	297
Total (Incl. 136 kg payload)	1458	1245	1134	1155	1186	1191
Vehicle Characteristics						
Rolling Res. Coeff	0.009	0.008	0.006	0.006	0.006	0.006
Drag Coeff.	0.33	0.27	0.22	0.22	0.22	0.22
Frontal Area (m^2)	2.0	1.8	1.8	1.8	1.8	1.8
Power for Auxiliaries (W)	700	1000	1000	1000	1000	1000
Engine						
Displacement (L)	2.50	1.79	1.65	1.11	1.75	1.16
Indicated Eff. (%)	38	41	41	41	51	51
Frictional ME Pressure (kPa)	165	124	124	124	153	153
Max. Engine Power (kW)	110	93	85	58	89	59
Max. Motor Power (kW)				29		30
Use of On-Board Fuel						
Driving Cycle						
US Urban (MJ/km)	2.82	2.00	1.78	1.20	1.53	1.03
US Highway (MJ/km)	2.06	1.45	1.25	0.91	1.04	0.78
US06 (MJ/km)	2.81	1.94	1.67	1.49	1.39	1.29
Combined (MJ/km) (4)	2.48	1.75	1.54	1.07	1.30	0.92
Combined (mpg) (8)	30.6	43.2	49.2	70.7	58.1	82.5
Combined as % Baseline	141	100	88	61	74	52
Life-Cycle Combined Energy						
Vehicle Operation (MJ/km)	2.47	1.75	1.55	1.07	1.31	0.92
Fuel Cycle (MJ/km) (5)	0.52	0.37	0.32	0.22	0.18	0.13
Vehicle Manufacturing (MJ/km)	0.29	0.25	0.25	0.26	0.26	0.26
Total (MJ/km)	3.28	2.37	2.12	1.55	1.75	1.31
Total as % Baseline	138	100	89	65	74	55
Life-Cycle Combined GHG Emissions						
Vehicle Operation (gC/km) (7)	48.5	34.4	30.2	21.0	27.1	19.1
Fuel Cycle (gC/km) (6)	12.1	8.6	7.6	5.2	4.3	3.0
Vehicle Manufacturing (gC/km)	5.5	4.8	4.8	5.0	5.0	5.1
Total (gC/km) (9)	66.1	47.8	42.6	31.2	36.4	27.2
Total as % of Baseline	138	100	89	65	76	57

Notes:
(1) 1 liter (0.737 kg) gasoline = 32.2 MJ (LHV)
(2) 1 liter (0.856 kg) diesel = 35.8 MJ (LHV)
(3) Propulsion system mass includes ICE, drive train, motors, battery, fuel (2/3 full), and tank
(4) Combined cycle is 55% urban/45% highway
(5) Fuel cycle energy, MJ per MJ fuel in tank: gasoline 0.21, diesel 0.14
(6) Fuel cycle gC per MJ fuel in tank = gasoline 4.9, diesel 3.3
(7) Vehicle operation gC per MJ burned = gasoline 19.6, diesel 20.8
(8) Gasoline equivalent miles per gallon calculated as equal fuel LHV
(9) gC of GHG calculated as C in CO_2 released plus carbon in CO_2 equal to 21 times mass of methane leaked

Table 9. Vehicles Using Fuel Cell Systems

	Hydrogen				Gasoline			
	Non-hybrid	**Non-hybrid**	**Hybrid**	**Hybrid**	**Non-hybrid**	**Non-hybrid**	**Hybrid**	**Hybrid**
	Comp.	Integrated	Comp.	Integrated	Comp.	Integrated	Comp.	Integrated
Mass (kg)								
Body & Chassis	776	780	752	754	821	822	775	776
Propulsion System (3)	465	479	372	378	638	640	460	463
Total (Incl. 136 kg payload)	1377	1395	1260	1268	1595	1598	1371	1375
Vehicle Characteristics								
Rolling Res. Coeff	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Drag Coeff.	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Frontal Area (m^2)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Power for Auxiliaries (W)	1000	1000	1000	1000	1000	1000	1000	1000
Propulsion System								
Max. Net Stack Power (kW)	103	105	63	63	120	120	69	69
Max. Motor Power (kW)	103	105	95	95	120	120	103	103
Use of On-Board Fuel								
Driving Cycle								
US Urban (MJ/km)	0.75	0.82	0.60	0.66	1.29	1.56	0.96	1.16
US Highway (MJ/km)	0.52	0.57	0.47	0.51	0.85	1.03	0.73	0.88
US06 (MJ/km)	0.92	1.00	0.78	0.87	1.51	1.83	1.27	1.56
Combined (MJ/km) (4)	0.65	0.71	0.54	0.59	1.10	1.32	0.86	1.04
Combined (mpg) (8)	117.3	106.5	140.3	128.1	69.2	57.4	88.4	73.1
Combined as % Baseline	37	41	31	34	62	75	49	59
Life-Cycle Combined Energy								
Vehicle Operation (MJ/km)	0.65	0.71	0.54	0.59	1.10	1.32	0.86	1.04
Fuel Cycle (MJ/km) (5)	0.50	0.55	0.42	0.46	0.23	0.28	0.18	0.22
Vehicle Mfg. (MJ/km)	0.31	0.32	0.28	0.28	0.33	0.33	0.28	0.28
Total (MJ/km)	1.46	1.58	1.24	1.33	1.66	1.93	1.32	1.54
Total as % Baseline	61	66	52	56	70	81	56	65
Life-Cycle Combined GHG Emissions								
Vehicle Operation (gC/km) (7)	0	0	0	0	21.5	26.0	16.8	20.3
Fuel Cycle (gC/km) (6)	23.3	25.6	19.4	21.3	5.4	6.5	4.2	5.1
Vehicle Mfg. (gC/km)	5.8	5.9	5.3	5.3	6.2	6.3	5.4	5.4
Total (gC/km) (9)	29.1	31.5	24.7	26.6	33.1	38.6	26.4	30.8
Total as % of Baseline	61	66	52	56	69	81	55	64

Notes:
(1) 1 liter (0.737 kg) gasoline = 32.2 MJ (LHV)
(2) 1 kg hydrogen = 120.0 MJ (LHV)
(3) Propulsion system mass includes fuel cell system, drive train, motors, battery, fuel (2/3 full), and tank
(4) Combined cycle is 55% urban/45% highway
(5) Fuel cycle energy, MJ per MJ fuel in tank: gasoline 0.21, hydrogen 0.77
(6) Fuel cycle gC per MJ fuel in tank = gasoline 4.9, hydrogen 36
(7) Vehicle operation gC per MJ burned = gasoline 19.6, hydrogen 0
(8) Gasoline equivalent miles per gallon calculated as equal fuel LHV
(9) gC of GHG calculated as C in CO_2 released plus carbon in CO_2 equal to 21 times mass of methane leaked

Table 10. Share of Life-Cycle Energy & GHG

Vehicle	Energy, % of Total			GHG, % of Total		
	Operation	Fuel Cycle	Vehicle Mfg.	Operation	Fuel Cycle	Vehicle Mfg.
2001 Reference	75	16	9	74	18	8
2020 Baseline	74	15	11	71	18	11
Gasoline ICE	73	15	12	72	18	10
Gasoline ICE Hybrid	69	14	17	67	17	16
Diesel ICE	75	10	15	74	12	14
Diesel ICE Hybrid	70	10	20	70	11	19
Hydrogen FC	45	34	21	0	81	19
Hydrogen FC Hybrid	44	35	21	0	79	21
Gasoline FC	67	14	19	66	16	18
Gasoline FC Hybrid	66	14	20	65	16	19

Note: Percentages for FCs are averages for “Component” and “Integrated” systems. Neither system varies more than about 1% from average. See Tables 8 & 9.

Table 11. On-Board Fuel Consumption of Hybrid Vehicles as Percentage of Non-Hybrid Vehicles

Vehicle	Driving Cycle			
	Combined	Urban	Highway	US06
Gasoline ICE	69	67	73	89
Diesel ICE	71	67	75	93
Hydrogen FC*	83	80	90	86
Gasoline FC*	78	74	86	85

*Differences between “component” and “integrated” systems are negligible.

Table 12. New vs. Previous Results

	On-Board Fuel Consumption per km, % of Baseline	
	Previous [1]	New
2020 Baseline	100	100
Gasoline ICE	88	88
Gasoline ICE Hybrid	61	61
Diesel ICE	77	74
Diesel ICE Hybrid	53	52
Hydrogen FC	--	37/41*
Hydrogen FC Hybrid	46	31/34*
Gasoline FC	--	62/75*
Gasoline FC Hybrid	86**	49/59*

* Components/Integrated
** Corrected

FIGURE 1. RELATIVE CONSUMPTION OF ON-BOARD FUEL ENERGY

- ■ MJ(LHV)/km as percentage of baseline vehicle fuel use
- ■ All other vehicles (except 2001 “reference”) are advanced 2020 designs
- ■ Driving cycle assumed is combined Federal cycles (55% urban, 45% highway)
- ■ Hatched areas for fuel cells show increase in energy use in integrated total system which requires compromises in performance of individual system components

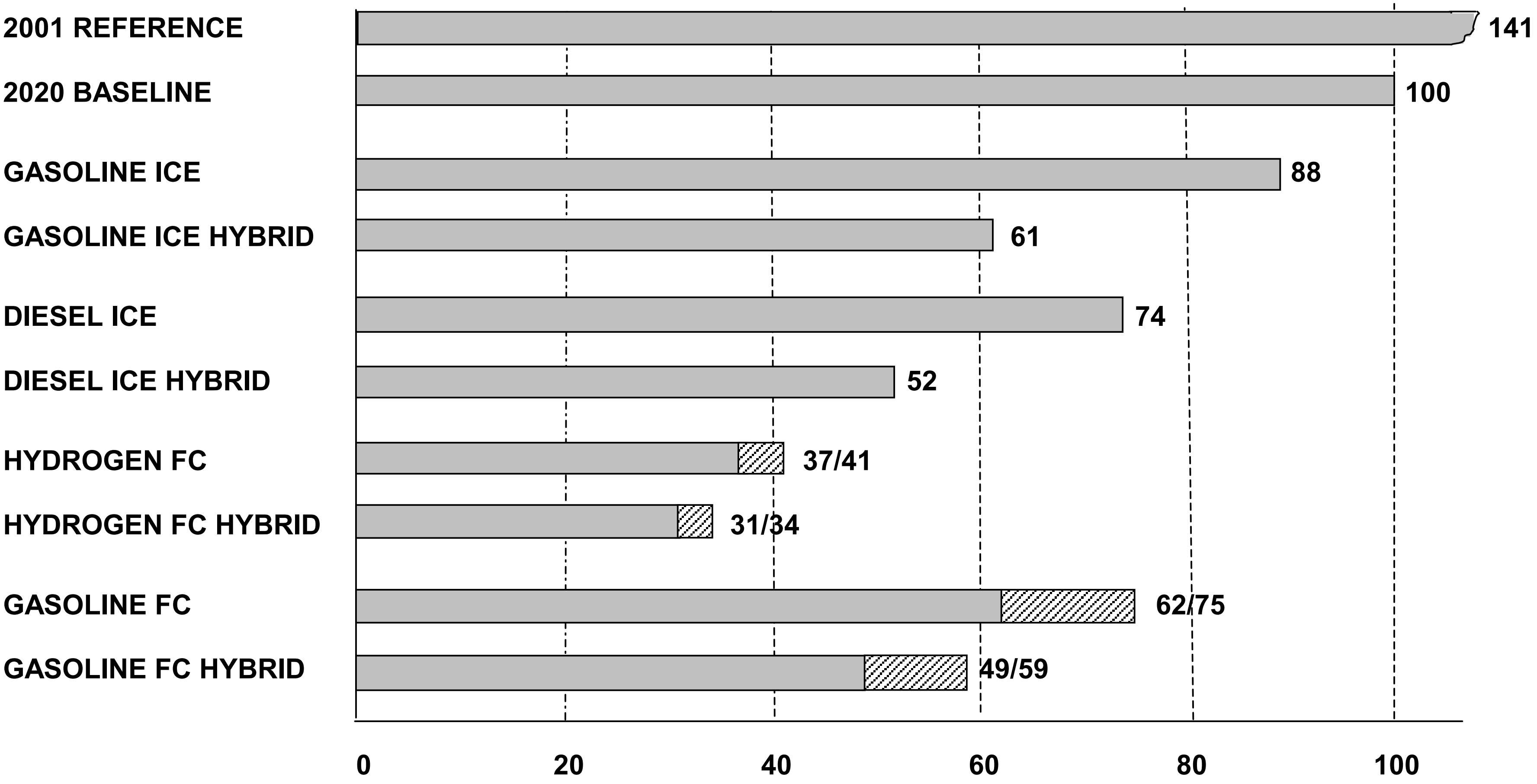

FIGURE 2. RELATIVE CONSUMPTION OF LIFE-CYCLE ENERGY

■ Total energy (LHV) from all sources consumed during vehicle lifetime
■ Shown as percentage of baseline vehicle energy consumption
■ Total energy includes vehicle operation and production of both vehicle and fuel

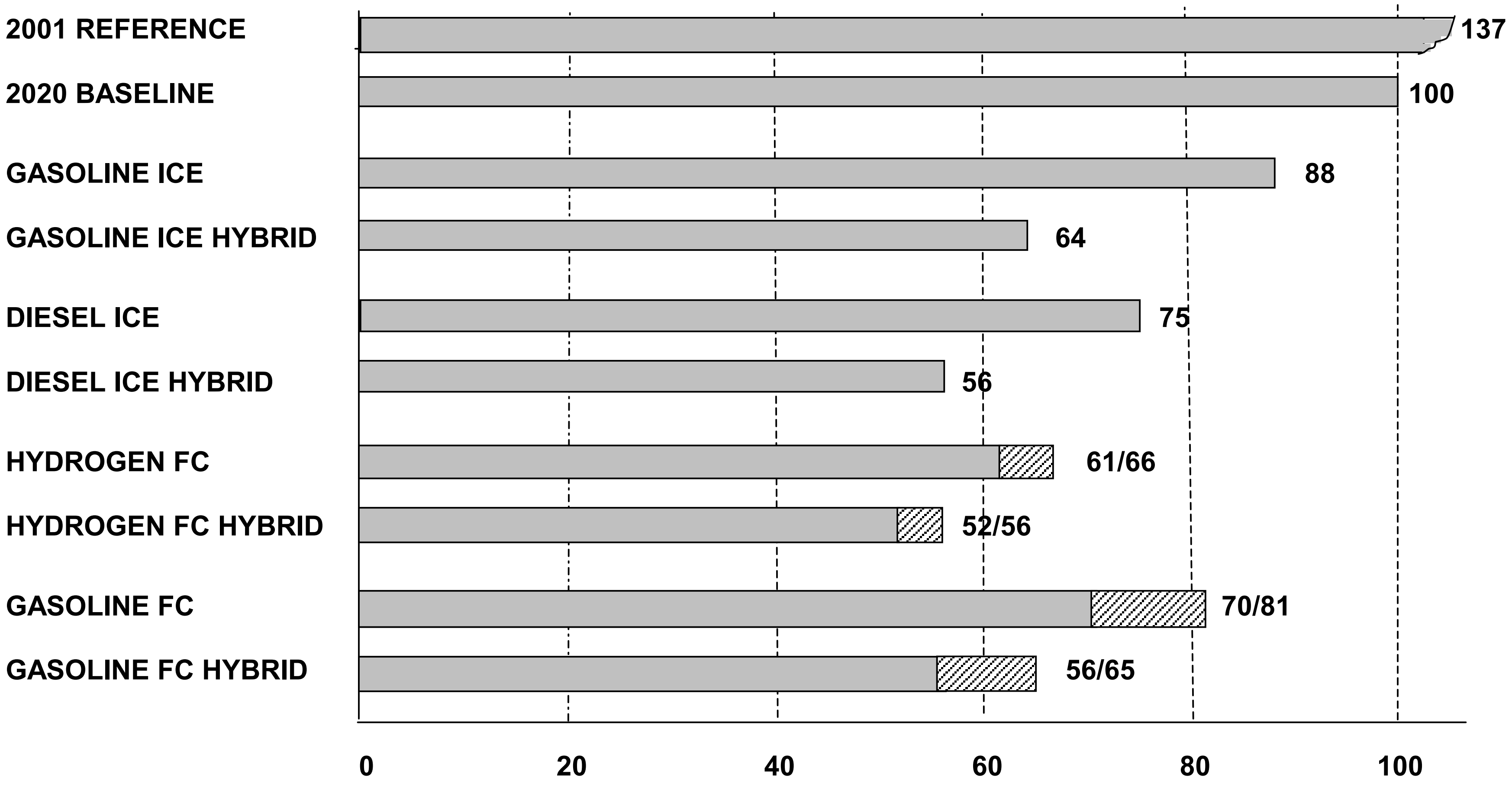

FIGURE 3. RELATIVE EMISSIONS OF LIFE-CYCLE GREENHOUSE GASES

- Mass of carbon equivalent emitted during vehicle lifetime
- Shown as percentage of baseline vehicle GHG emissions
- Greenhouse gases include only CO_2 and CH_4 (carbon assumed to be 21 CO_2)
- Emissions include vehicle operation and production of both vehicle and fuel