structure. Integrating sustainable energy systems into the infrastructure would allow rapid adoption of electrolysis-based hydrogen production, whenever these future transportation systems become viable. Since the 1930s, the recognized vision of the hydrogen economy has been to allow the storage of electrical energy, reduce environmental emissions, and provide a transportation fuel. This goal is clearly achievable, but only with a sustained, focused effort.

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16. These figures are from the Energy Information Administration, available at www.eia.doe.gov/cneaf/electricity/epm/tablees1a.html.
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VIEWPOINT

Hybrid Cars Now, Fuel Cell Cars Later

Nurettin Demirdöven[1] and John Deutch[2]*

We compare the energy efficiency of hybrid and fuel cell vehicles as well as conventional internal combustion engines. Our analysis indicates that fuel cell vehicles using hydrogen from fossil fuels offer no significant energy efficiency advantage over hybrid vehicles operating in an urban drive cycle. We conclude that priority should be placed on hybrid vehicles by industry and government.

Our interest in moving toward a hydrogen economy has its basis not in love of the molecule but in the prospect of meeting energy needs at acceptable cost, with greater efficiency and less environmental damage compared to the use of conventional fuels. One goal is the replacement of today's automobile with a dramatically more energy-efficient vehicle. This will reduce carbon dioxide emissions that cause adverse climate change as well as dependence on imported oil. In 2001, the United States consumed 8.55 million barrels of motor gasoline per day (*1*), of which an estimated 63.4% is refined from imported crude oil (*2*). This consumption resulted in annual emissions of 308 million metric tons (MMT) of carbon equivalent in 2001, accounting for 16% of total U.S. carbon emissions of 1892 MMT (*3*).

Two advanced vehicle technologies that are being considered to replace the current fleet, at least partially, are hybrid vehicles and fuel cell (FC)–powered vehicles. Hybrid vehicles add a parallel direct electric drive train with motor and batteries to the conventional internal combustion engine (ICE) drive train. This hybrid drive train permits significant reduction in idling losses and regeneration of braking losses that leads to greater efficiency and improved fuel economy. Hybrid technology is available now, although it represents less than 1% of new car sales. FC vehicles also operate by direct current electric drive. They use the high efficiency of electrochemical fuel cells to produce power from hydrogen. For the foreseeable future, hydrogen will come from fossil fuels by reforming natural gas or gasoline. FC vehicle technology is not here today, and commercialization will require a large investment in research, development, and infrastructure (*4*).

Here, we evaluate the potential of these advanced passenger vehicles to improve energy efficiency. We show that a tremendous increase in energy efficiency can be realized today by shifting to hybrid ICE vehicles, quite likely more than can be realized by a shift from hybrid ICE to hybrid FC vehicles.

Energy Efficiency Model

To provide a basis for comparison of these two technologies, we use a simple model (*5*) for obtaining the energy efficiency of the various power plant–drive train–fuel combinations considered in more detailed studies (*6–11*). In general, the energy efficiency of ICEs with a hybrid drive train and from FC-powered vehicles vary depending on the vehicle configuration and the type of engine, drive train, and fuel (natural gas, gasoline, or diesel).

For each configuration, we determine well-to-wheel (WTW) energy efficiency for a vehicle of a given weight operating on a specified drive cycle. The overall WTW efficiency is divided into a well-to-tank (WTT) and tank-to-wheel (TTW) efficiency so that WTW = WTT × TTW.

We begin with the U.S. Department of Energy (DOE) specification of average passenger energy use in a federal urban drive cycle, the so-called FUDS cycle (*12*). For example, for today's ICE vehicle that uses a spark ignition engine fueled by gasoline, the TTW efficiency for propulsion and braking is 12.6% (Fig. 1A).

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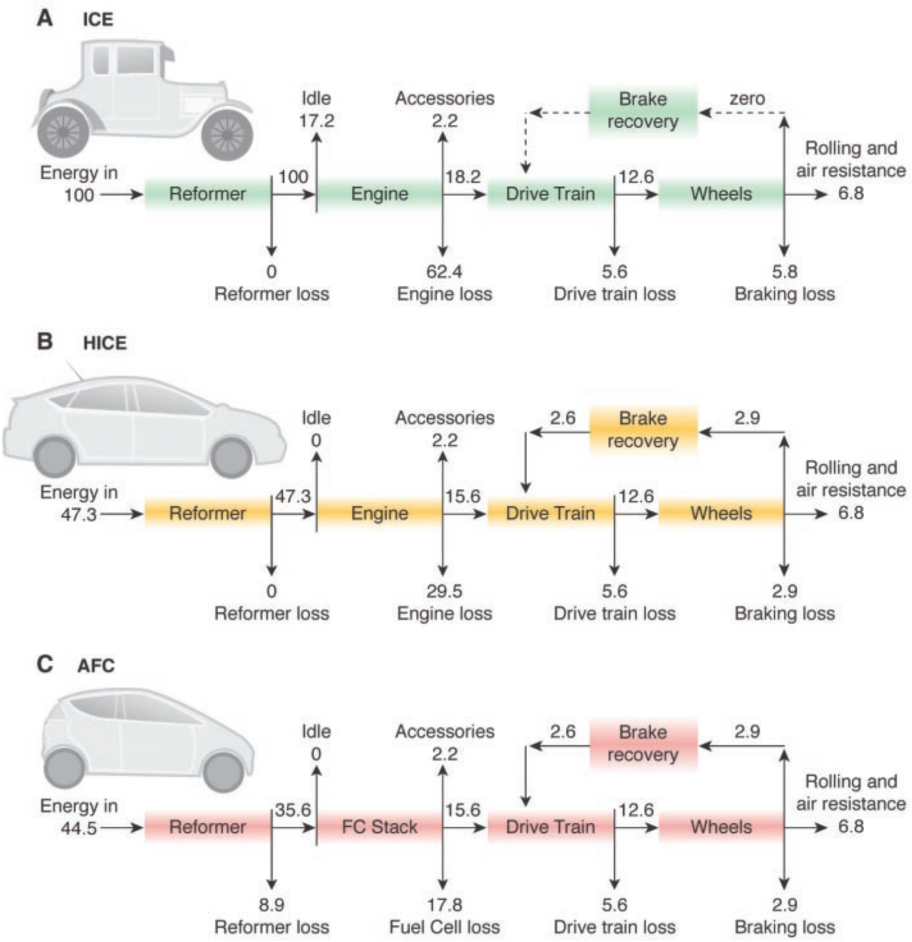


Fig. 1. Energy flow for various vehicle configurations. (**A**) ICE, the conventional internal combustion, spark ignition engine; (**B**) HICE, a hybrid vehicle that includes an electric motor and parallel drive train which eliminates idling loss and captures some energy of braking; (**C**) AFC a fuel cell vehicle with parallel drive train. The configuration assumes on-board gasoline reforming to fuel suitable for PEM fuel cell operation.

The TTW efficiency of other configurations is estimated by making changes in the baseline ICE parameters and calculating energy requirements beginning with energy output. A hypothetical hybrid ICE (HICE), based on current hybrid technology, that completely eliminates idling losses and captures a portion (50%) of braking losses for productive use (*13*) will have a TTW efficiency of 26.6% (Fig. 1B). Both the ICE and the HICE use gasoline fuel directly, so no fuel processing is needed.

A likely hydrogen-based car might be a proton-exchange membrane (PEM) FC-powered vehicle with a hybrid power train. This advanced fuel cell (AFC) vehicle has an on-board fuel processor that reforms gasoline to hydrogen fuel suitable for feed for the PEM fuel cell. We assume a reformer efficiency of 80% and 50% efficiency for the FC stack operating over the urban drive cycle. We include a power train with the same characteristics as the HICE vehicle. The TTW efficiency of this configuration is 28.3% (Fig. 1C).

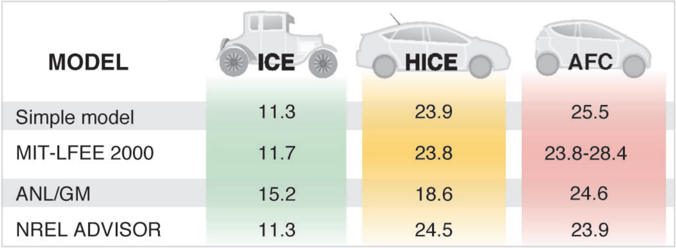
It is apparent that any alternative vehicle configuration of fuel–power plant–drive train can be considered in a similar fashion. For example, if hydrogen were available without energy cost, the overall efficiency would improve to 39.0%, over three times that for the conventional ICE (*14*). A diesel ICE with a hybrid power train could achieve an efficiency of 31.9%, assuming that this higher compression direct-injection engine has an efficiency of 45.0% compared to 37.6% for the gasoline ICE.

Our results (Fig. 2) are in reasonably good agreement with those of more detailed studies but do not require elaborate simulation models. Figure 2 shows that, except for the Argonne National Laboratory/General Motors (ANL/GM) (*6*) study, the relative gain in efficiency in moving from an ordinary ICE to a HICE is more than twofold. The reason for this difference is not clear, because the TTW analysis in that study has its basis in a GM proprietary simulation model.

Validating Our Model

To test the validity of these comparisons and our simple model, we have used an advanced vehicle simulator called ADVISOR, developed by the National Renewable Research Laboratory (NREL) of DOE (*15*). ADVISOR provides estimates of energy efficiencies for different vehicle configurations. ADVISOR shows the broad range of vehicle performance that is possible with a reasonable choice of system parameters such as maximum engine power, maximum motor power, transmission type, and brake energy regeneration. The parameters we selected for the simulation of the ICE, HICE, and AFC are given in Table 1; for comparison, TTWs based on this simulation are 28.8% for the Toyota Prius and 26.2% for the Honda Insight. Except for the ANL/GM results, all studies point to large potential energy efficiency gains from hybrid vehicles in urban drive cycles compared to cars with conventional ICEs (*16*).

Our analysis shows that hybrids offer the potential for tremendous improvement in energy use and significant reduction in carbon emissions compared to current ICE technology. But hybrid vehicles will only be adopted in significant quantities if the cost to the consumer is comparable to the conventional ICE alternative. Hybrid technology is here today, but, of course, hybrid vehicles cost more than equivalent ICE vehicles because of the parallel drive train. Estimates of the cost differential vary, but a range of $1000 to $2000 is not unreasonable. Depending on the miles driven, the cost of ownership of a hybrid vehicle may be lower than a conventional ICE, because the discounted value of the fuel saving is greater than the incremental capital cost for the parallel drive train and



MODEL	ICE	HICE	AFC
Simple model	11.3	23.9	25.5
MIT-LFEE 2000	11.7	23.8	23.8-28.4
ANL/GM	15.2	18.6	24.6
NREL ADVISOR	11.3	24.5	23.9

Fig. 2. Comparison of WTW energy efficiencies of advanced vehicle systems using gasoline fuel. Color coding follows that in Fig. 1. 90% WTT efficiency in all cases; thus WTW = 0.90 TTW. Data for ICE and HICE is from (*7*), table 5.3. Data for AFC is from (*8*), which does not give energy efficiency directly. We derive a range for energy efficiency by comparing data in tables 8 and 9 for MJ/km for vehicle and fuel cycle for the 2020 ICE hybrid to that of the gasoline FC hybrid given in (*7*), table 5.3. Data from (*6*), table 2.1. Data from NREL's ADVISOR simulation; for details, see Table 1.

Table 1. Input and output vehicle parameters obtained from NREL's ADVISOR simulations. We assumed 1500 kg for the total vehicle weight, including two passengers and fuel on board. The actual weights of the Toyota Prius and Honda Insight with two passengers and fuel on board are 1368 kg and 1000 kg, respectively. Auxiliary power is 700 W except for the Honda Insight, for which it is 200 W. The simulations are over a FUDS cycle. Fuel use and TTW calculations follow the definition of efficiency given in (*5*), which is different than the "overall system efficiency" defined in the NREL's ADVISOR. Of course, the underlying performance is the same.

	ICE	HICE	AFC	Prius	Insight
			Vehicle		
Max power (kW)	102	83	70	74	60
Power:weight ratio (W/kg)	68	55	47	54	60
Frontal area (m^2)	2	2	2	1.75	1.9
Rolling resistance coefficient	0.009	0.009	0.009	0.009	0.0054
			Engine–motor–fuel cell stack		
Max engine power (kW)	102	43		43	50
Max engine efficiency (%)	38	38		39	40
Max motor power (kW)		40	40	31	10
Max motor efficiency (%)		92	92	91	96
Max fuel cell power (kW)			30		
Max fuel cell stack efficiency (%)			56		
			Acceleration		
Time for 0 to 60 mph (s)	18	10	13	15	12
			Fuel use		
Fuel energy use (kJ/km)	3282	1536	1553	1317 (1274)	1189 (982)
Fuel economy (mpg)	21	44	43	53	69
			Average efficiencies (%)		
Engine efficiency	21	30		28	25
Motor efficiency		79	84	81	90
Reformer efficiency			80		
Fuel cell stack efficiency			51		
Round-trip battery efficiency		100	84	81	82
Transmission efficiency	75	75	93	100	92
Regenerative braking efficiency		35	39	41	38
TTW efficiency	12.6	27.2	26.6	28.8	26.2

electric motor. Thus, hybrid vehicles can con tribute to lower emissions and less petroleum use at small or negative social cost (*17*). Today only Toyota and Honda offer hybrids in the United States; DaimlerChrysler, Ford, and General Motors are planning to introduce hybrids in the period from 2004 to 2006. At present there is a federal tax credit of $1500 for purchase of a hybrid vehicle, but it is scheduled to phase out in 2006 (*18*).

Fuel cell technology is not here today. Both the Bush Administration's FreedomCAR program and the earlier Clinton Administration Partnership for a New Generation of Vehicles (PNGV) launched major DOE research and development initiatives for FC-powered vehicles. The current FreedomCAR program "focuses government support on fundamental, high-risk research that applies to multiple passenger-vehicle models and emphasizes the development of fuel cells and hydrogen infrastructure technologies" (*19*). A successful automotive FC program must develop high-durability FC stacks with lifetimes of 5 to 10 thousand hours, well beyond today's experience. It is impossible to estimate today whether the manufacturing cost range that FC stacks must achieve for economical passenger cars can be reached even at the large-scale production runs that might be envisioned.

The government FC research and development initiative is welcome, but it is not clear whether the effort to develop economic FC power plants for passenger cars will be successful. In parallel, we should place priority on deploying hybrid cars, beginning with today's automotive platforms and fuels. If the justification for federal support for research and development on fuel cells is reduction in imported oil and carbon dioxide emissions, then there is stronger justification for federal support for hybrid vehicles that will achieve similar results more quickly. Consideration should be given to expanding government support for research and development on generic advanced hybrid technology and extending hybrid vehicle tax credits.

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$$E_{in} = \frac{1}{\eta_{fp}\eta_{e}}\left[\frac{E_{out}}{\eta_{dt}} - B\eta_{rb} + E_{ac} + E_{idle}\right]$$
where E_{idle} and E_{ac} are the energies required in the specified drive cycle for idling and for accessories, respectively. B is the recovered braking energy. The various efficiencies of different stages are η_{fp}, η_{e}, η_{dt}, and η_{rb} for fuel processing, engine or fuel cell, drive train, and regenerative braking, respectively. We focus on efficiency rather than the more common fuel economy because the efficiency is less sensitive to vehicle weight than fuel economy.
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14. For this case, there is no processor loss, and the FC stack efficiency improves to 55% because the FC functions better on pure hydrogen than reformate.
15. The NREL ADVISOR simulator is described online at www.ctts.nrel.gov/analysis. Use of the model is described in several publications at www.ctts.nrel.gov/analysis/reading_room.html; see, for example, (*20*, *21*).
16. GM quotes 15 to 20% fuel economy improvements in 2007 for hybrid Tahoe and Yukon sport utility vehicles. Not surprisingly, Toyota seems more optimistic about hybrids than GM.
17. In Europe, where fuel prices are much higher than in the United States, the advantage of hybrids over conventional ICEs is significantly greater.
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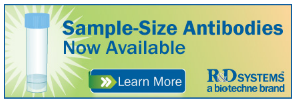

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