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Science 305, 974 (2004);
DOI: 10.1126/science.1093965

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TOWARD A HYDROGEN ECONOMY

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.

References and Notes
1. For the purpose of this discussion, I use the following definition of the hydrogen economy: the production, storage, distribution, and use of hydrogen as an energy carrier.
15. In any discussion concerning the efficiency of electrolyzers, it is appropriate to use the higher heating value to calculate the efficiency. This corresponds to the isothermal potential (1.47 V — 39 kWh/kg) and represents the assumption that all the energy needed to split water comes from the electricity.
16. These figures are from the Energy Information Administration, available at www.eia.doe.gov/cneaf/electricity/epm/tablea1a.html.
17. For an estimate of the amount of water needed for hydrogen-powered fuel cell vehicles, we will assume a vehicle fuel economy of 60 miles per kg of H2, that vehicle miles traveled $= 2.6 \times 10^{12}$ miles/year [found at www.bts.gov/publications/national_transportation_statistics/2002/html/table_automobile_profile.html], and that 1 gallon of water contains 0.42 kg of H2. Total water required for the U.S. fleet = $(2.6 \times 10^{12} \text{miles/year}) (1 \text{kg of H}_2/60 \text{miles}) (1 \text{gal H}_2O/0.42 \text{kg of H}_2) = 1 \times 10^{11} \text{gallons of H}_2O/\text{year}$. This represents the water used directly for fuel. If one considers all water uses along the chain; for example, from construction of wind farms to the electrolysis systems (life cycle assessment), then the total water use would be in the range of $3.3 \times 10^{11} \text{gallons H}_2O/\text{year}$.
18. This is a life cycle analysis [M. Mann and M. Whitaker, unpublished data]. The United States used about 126 billion gallons of gasoline in 2001 [see link in (17)].
25. Contributions by D. Sander for careful manuscript edits and by J. Iry for Fig. 1 are gratefully acknowledged.

VIEWPOINT

Hybrid Cars Now, Fuel Cell Cars Later

Nurettin Demirdöven and John Deutch

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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\footnotetext[3]{To whom correspondence should be addressed. E-mail: jmd@mit.edu}
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 to the PEM fuel cell. We assume a reformer 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

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).

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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 TTT 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.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>ICE</th>
<th>HICE</th>
<th>AFC</th>
<th>Prius</th>
<th>Insight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max power (kW)</td>
<td>102</td>
<td>83</td>
<td>70</td>
<td>74</td>
<td>60</td>
</tr>
<tr>
<td>Power:weight ratio (W/kg)</td>
<td>68</td>
<td>55</td>
<td>47</td>
<td>54</td>
<td>60</td>
</tr>
<tr>
<td>Frontal area (m²)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1.75</td>
<td>1.9</td>
</tr>
<tr>
<td>Rolling resistance coefficient</td>
<td>0.009</td>
<td>0.009</td>
<td>0.009</td>
<td>0.009</td>
<td>0.0054</td>
</tr>
<tr>
<td>Max engine power (kW)</td>
<td>102</td>
<td>43</td>
<td>43</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Max engine efficiency (%)</td>
<td>38</td>
<td>38</td>
<td>39</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Max motor power (kW)</td>
<td>40</td>
<td>40</td>
<td>31</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Max motor efficiency (%)</td>
<td>92</td>
<td>92</td>
<td>91</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Max fuel cell power (kW)</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max fuel cell stack efficiency (%)</td>
<td>56</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Acceleration
| Time for 0 to 60 mph (s) | 18 | 10 | 13 | 15 | 12 |
| Fuel use | | | | | |
| Fuel energy use (kJ/km) | 3282 | 1536 | 1553 | (1274) | (982) |
| Fuel economy (mpg) | 21 | 44 | 43 | 53 | 69 |
| Average efficiencies (%) | 21 | 30 | 28 | 25 |
| Engine efficiency | 79 | 84 | 81 | 90 |
| Motor efficiency | 80 | | | |
| Reformer efficiency | 51 | | | |
| Fuel cell stack efficiency | 100 | 84 | 81 | 82 |
| Round-trip battery efficiency | 75 | 75 | 93 | 100 | 92 |
| Transmission efficiency | 35 | 39 | 41 | 38 |
| Regenerative braking efficiency | 12.6 | 27.2 | 26.6 | 28.8 | 26.2 |

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.

References and Notes
4. Only gasoline and natural gas are widely available as a transportation fuel today; a hydrogen or methanol fueled transportation system would take decades to deploy, at significant cost.
5. We define the average energy efficiency as the ratio of the energy needed at the wheels, $E_{\text{out}}$, to drive and brake a car of a given weight, $M$, on a specified test cycle to the total fuel energy, $E_{\text{in}}$, needed to drive the vehicle. Regenerative braking, if present, reduces the fuel needed to drive the car. Accessory power is not included in energy output. The TTT efficiency is calculated as $\eta_{\text{TTW}} = E_{\text{out}} / E_{\text{in}}$. For the vehicle configurations in Fig. 1, we keep $E_{\text{out}}$ constant and calculate $E_{\text{in}}$ by backward induction as $E_{\text{in}} = -\frac{1}{\eta_{\text{TTW}}} E_{\text{out}} + \eta_{\text{diesel}} + \eta_{\text{fuel}} + \eta_{\text{air}} + E_{\text{aux}}$.

13. We wish to keep the presentation of our model simple. The assumption of complete regenerative braking and reduction in idling losses is not realistic. However, improvement in ICE engine efficiency is also possible (7). The current performance of hybrid ICE passenger vehicles such as the Toyota Prius is impressive. Toyota reports TTT efficiency of the Prius as 32%, compared to 16% for a conventional ICE: www.toyota.co.jp/en/tech/environment/fcv/fcv12.html. Prius regenerative braking reportedly recaptures 30%; see www.ott.de/does/hev/regenerative.html.
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.
18. The 2003 Energy Act, currently under consideration by Congress, would extend the time period for the hybrid car tax credit.
22. This work was supported by the Alfred P. Sloan Foundation.