Environmental Protection Agency standards. Indeed, environmental regulation as a key driver of intermediate-term R&D is an important issue. However, we emphasize the converse—that emerging technological realities should drive enlightened regulation. Too often, that is not the case. The PNGV program, driven principally by fuel efficiency, was hampered by inadequate coordination between technological and regulatory development. Remedying that situation requires either more effective interagency coordination or enhanced technological capability at EPA. It is unclear which of those two remedies is more easily achievable.

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Joan Ogden's otherwise informative article does not explain exactly why a hydrogen economy should be preferred over the conventional economy based on direct use of fossil fuels. The article suggests that, because nuclear power and renewable energy sources (hydropower, solar, and wind) are not expected to expand enough to support the electrolysis of seawater globally, the only realistic source for hydrogen fuel is through the reforming of petroleum or natural gas.

The process for extracting hydrogen from fossil hydrocarbons—using very hot steam, for example—will produce as much carbon dioxide as if the fuel had been burned conventionally. If that CO_2 is not sequestered by some means, preferably near the hydrogen plant, its release into the atmosphere will cause as much global warming as if it had come from a conventional car or thermal power plant.

Hydrogen fuel cells do have an advantage over fossil fuels in that they produce no nitrogen oxides or particulate pollution, but improvements to conventional combustion technology have already eliminated those pollutants to a large extent. Seemingly, then, the only reason to switch to a hydrogen-based economy would be the superior energy efficiency of fuel cells, although it is not clear how much savings will remain after inefficiencies in the reforming process are factored in.

Perhaps the global environment would be better served if we tackle a much simpler problem—extending carbon sequestration technologies, already under development for large thermal plants, down to the scale of the smallest combustion engines. We could then continue with the current infrastructure for fossil-fuel distribution and use, while avoiding the complications of producing, distributing, and storing a radically new fuel.

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The article by Joan Ogden proposes that available hydrogen technologies can address future energy and environmental challenges. More energy, though, is needed to produce a quantity of hydrogen than can be obtained from it by combustion or by reactions in a fuel cell. Alternative fuels such as hydrogen and methanol are actually energy storage media or secondary energy carriers rather than fuels in the traditional sense. Ordinarily, we think of fuels as substances that, when burned, release more energy than is required to produce them. In addition to specifying the heat of combustion of an alternative fuel, giving its production energy value would also be helpful—and would require specifying the process of production.

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In the US, 90–95% of hydrogen is produced by steam reforming, a chemical process that makes hydrogen from a mixture of water and a hydrocarbon feedstock. Theoretically, the energy that must be supplied to the process is the difference between the heat of combustion of the resulting hydrogen and the heat of combustion of the reformed feedstock. This difference sets the lower limit on the energy required to produce an alternative fuel. In practice, the overall efficiency of the process—that is, the energy content of the hydrogen produced divided by the total energy consumed by the reforming process—is approximately 65%.[1] The efficiency of the more costly electrolysis process is approximately the same (62.5%), although some commercial producers claim efficiencies as high as 80%. In other words, to produce an amount of hydrogen with the energy content of 1 MJ, about 1.6 MJ of energy must be expended. But only 0.167 MJ of energy must be expended to produce a quantity of gasoline with an energy content of 1 MJ; there is thus a substantial gain of available energy.[2]

The US Census Bureau reports that 132 million cars were registered in the US in 1999, and those cars used 73.2 billion gallons, or 208×10^9 kg of gasoline. Using the value for the high heat of combustion for gasoline of 47.3 MJ/kg or 13.14 kWh/kg, this amounts to a total of 2.73×10^9 MWh. With an overall efficiency of 25% for automobiles with internal combustion engines, 682×10^6 MWh is actually used for propulsion. With a fuel-cell efficiency of 50% and electric motor efficiency of 90%, the energy supplied to fuel-cell-powered cars would have to be at least 1.52×10^9 MWh.

The amount of hydrogen with this energy content is 115.7×10^9 kg. Producing that much hydrogen requires 262×10^9 kg of octane, or about 92.3×10^9 gallons of gasoline, somewhat more than the quantity now used by US automobile traffic, as noted previously. Clearly, use of hydrogen produced by reformation does not free us from dependence on hydrocarbons.

To produce hydrogen with 1.52×10^9 MWh energy content by electrolysis would, according to the hydrogen production efficiency value of 62.5%, require 2.42×10^9 MWh. The total generation of electrical energy in the US in 1999 was 3.68×10^9 MWh, with the winter peak load of 849 GW, according to the Census Bureau. US electrical energy production would have to be increased by at least 65% to supply enough energy for those 132 million US autos to be fuel-cell–powered. If the power plants ran 24 hours a day to supply electrical energy for the electrolyzers, their capacity would have to be 276 GW above the existing generating capacity. If electrolyzers were to operate off peak, proportionally higher additional capacity would have to be installed to meet the demand. Most US power plants are fueled by coal, fuel oil, and natural gas, the only fuels available in sufficient quantities to meet the demand. Nuclear energy appears to be out of the question because of prejudice and possibly because personnel who would conscientiously operate nuclear power plants may not be available on the scale needed.

The prospects for solar energy, frequently offered as a solution, do not appear encouraging. The stated goal of the US Department of Energy was to achieve a capacity of 1400 MW from US-made photovoltaic systems worldwide by the year 2000. Compare this to the 849 GW of US winter peak load. Photovoltaic installations on the scale required for hydrogen production may also have problems with the toxicity of their metallic components. Therefore, an environmental impact assessment of the recycling and disposal of photovoltaic cells is desirable.

References

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Ogden replies: Dan Cohn and John Heywood raise the issue of allocation of R&D resources among short-term and long-term concepts. Analysis by our group at Princeton University and other researchers suggests that, even under optimistic assumptions about, it would be several decades before hydrogen fuel-cell vehicle technologies could make a globally significant impact on reducing emissions. We agree that it is very important in the near term to encourage use of more efficient, less polluting internal combustion engine technologies using conventional fuels.

Still, hydrogen holds the greatest long-term promise for dealing simultaneously with air pollution, greenhouse gas emissions, and energy supply diversity. With hydrogen fuel-cell vehicles, emissions could be reduced significantly compared to those from advanced internal combustion engine vehicles.

It is highly uncertain today what economic values should be assigned to external costs of energy (such as climate change, health effects from air pollution, oil supply insecurity). However, the trend of the past few decades has been toward ever-increasing regulation of emissions, and integrated assessment models of global climate change suggest that deep reductions in carbon emissions from energy use will be required to stabilize atmospheric carbon dioxide at acceptable levels. Depending on how we ultimately value the external costs of energy, hydrogen might become the long-term fuel of choice.

Should long-term concepts like hydrogen and fuel-cell vehicles have high priority, given that relatively modest improvements in more traditional internal combustion engine technologies could help address environmental and energy supply problems much sooner? In my view, hydrogen and fuel-cell technologies, although high-risk and long-term, have a potentially very high payoff. Therefore, they deserve significant government support now, as "insurance," so that they will be ready in a few decades, if and when we need to deploy them widely.

Rather than curtailing research on long-term technologies, I encourage a comprehensive strategy: Develop clean, efficient internal combustion engine vehicles in the near term, coupled with a long-term strategy of R&D on hydrogen and fuel cells. Consistent policies to encourage use of cleaner transportation systems