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Fuel Cells:
A Competitive Market Tool for Carbon Reductions

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ABSTRACT:

Fuel cells are rapidly evolving as a viable, variable-scale distributed electricity generation technology that can use hydrogen derived from a host of fuel resources, ranging from fossil fuels to renewables. Coupled with their high operating efficiency, fuel cells have attracted a great deal of attention in the global warming literature for their promise in reducing future emissions of carbon dioxide. This paper examines the potential for reducing emissions of greenhouse gases through the use of fuel cells as a distributed electricity generation source and as a source of power for electric vehicles. We investigate the economics and carbon reduction potential of various scenarios that we believe shed light on the potential of these technologies to reduce carbon emissions over the long term. Our analysis explicitly recognizes that fuel cells will experience competition from other energy technologies, and therefore, fuel cells will need to economically compete against these other technologies to obtain market share.

INTRODUCTION

The Conference of the Parties (COP III) meeting in December 1997 in Kyoto established a good-faith target for reductions of greenhouse gas emissions for the United States of 7% between 2008-2012, using 1990 emissions as a baseline. Other developed nations' targets ranged from 5-8% (UNFCC 1997). All nations involved in the agreement are presently contemplating strategies for achieving these reductions.

Coincident with these efforts, the electric and gas utilities in the United States and in other leading industrialized nations are undergoing profound changes under a process known as restructuring. One of the expected outcomes of this activity is movement towards a system of smaller, more distributed sources of power generation.

These two trends parallel a rapid rate of development in fuel cell technology, which may offer attractions to both. The fuel cell is an extremely clean, highly efficient electricity generation technology that can use hydrogen derived from any of a variety of sources, including low- or no-carbon sources. Fuel cells are hence being widely touted as one of the key technologies for addressing global energy and environmental issues into the foreseeable future. Fuel cells are also modular and easily sized for individual applications, while being extremely reliable, quiet, and relatively low-maintenance. All of this makes them ideal candidates for distributed power applications; however, they are still so relatively new (only one company thus far even offers a commercial unit) that studies of their likely market penetration and impacts are comparatively few.

This paper examines the potential for reducing emissions of greenhouse gases through the use of fuel cells as a distributed electricity generation source. We investigate the economics and carbon reduction potential of various scenarios that we believe shed light on the potential of these technologies to reduce carbon emissions over the long term. Our analysis explicitly recognizes that fuel cells will experience competition from other energy technologies and, therefore, will need to economically compete against these other technologies to obtain market share.

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A Brief Description of Fuel Cells and Hydrogen Fuel

Fuel cells are electrochemical devices containing a cathode, anode, and electrolyte in which free molecular hydrogen is combined with oxygen to form water. Energy released in this process is partially captured as a flow of electricity through an external circuit, and the remainder given off as heat. In a sense, fuel cells operate in a similar manner to batteries except that the fuel (hydrogen) and oxidant (oxygen) are delivered from outside the fuel cell housing. Most current fuel cell designs derive their oxygen from ambient air.

Hydrogen used by the cell can come from a great variety of sources. The most readily available source of hydrogen today is methane (the principal component of natural gas), and indeed most hydrogen produced today is derived from methane (Thomas et al 1997). Many fuel cell applications presently under development therefore target natural gas as their design fuel source.

Hydrogen may also be obtained from partial oxidation of other hydrocarbon-based fuels like petroleum or coal. Various research programs around the world are directed at investigating the production of hydrogen from coal through, for example, the water-gas shift reaction (a process for converting low-quality synthesis gas into higher-quality fuels: $CO + H_2O \rightarrow H_2 + CO_2$).

Hydrogen can also be produced from renewable biofuel feedstocks. Methane is generated during the decomposition of biological materials such as agricultural byproducts or municipal solid wastes. Anaerobic digestion systems combined with electricity generation technologies have allowed many agricultural operations to become energy self-sufficient and even net electricity producers, although to date these operations typically employ simple combustion and energy recovery technologies.

Hydrogen can also be produced through the electrolysis of water; however, in its current level of development this process is quite expensive and therefore uneconomic for widespread application (see, for example, NREL 1995). Continuing research into relevant areas such as photo-assisted or photo-enhanced electrolysis (catalyzed by a combination of sunlight and noble metals) may make this a viable source of hydrogen in the future.

Fuel Cells and Carbon Emissions

Unlike conventional combustion technologies, which capture energy released by the break-up of carbon-hydrogen bonds, fuel cells capture energy by the oxidation of hydrogen (i.e., the chemical combination of hydrogen and oxygen into water). As noted, currently the most commonly derived form of hydrogen is from methane, so that steam reforming or other fuel processing required to break the carbon-hydrogen bonds produces carbon in addition to hydrogen.

In current practice, this carbon is generally vented to the atmosphere; hence, using fossil fuels for producing hydrogen ultimately results in carbon emissions just as combusting them directly. Fuel cells still offer a number of other advantages over most conventional combustion technologies, due in part to very high operating efficiencies, particularly when heat recovery is employed. Incorporating fuel cells into a distributed power generation system might also offer efficiency gains by largely eliminating electricity transmission losses and their associated costs and emissions. Finally, because the break-up of carbon-hydrogen bonds in fossil fuels is not the source of energy used in fuel cells, this separation can be undertaken in a central location apart from the fuel cell in conjunction with carbon sequestration, with only the hydrogen or hydrogen-rich gas ultimately delivered to the fuel cell (or system of fuel cells). Such a system of central hydrogen production/sequestration facilities coupled with fuel cells contains tremendous potential for carbon emissions reductions, even though still based on fossil fuels.

Hydrogen derived from biomass fuels goes even further in terms of carbon reduction potential by offering a net zero addition of carbon to the atmosphere. This is because any carbon released from biomass conversion is later recaptured during a future biomass growth cycle. Combining biomass fuel use for hydrogen production with separate sequestration, with final conversion to electricity through fuel cells, could even enable a net negative carbon emission (i.e., carbon extraction) from the atmosphere.

Modeling Hydrogen Production and Fuel Cells 1990-2095

In order to carry out our analysis of the performance of fuel cells and the impact that they might make in reducing carbon emissions, we employ the energy, agricultural-land-use, and carbon cycle components and concentrations of the MiniCAM model, version MiniCAM 98.3. MiniCAM 98.3 is an integrated assessment model of global change with a focus on the world's energy and agriculture systems. This is an updated version of the MiniCAM model described in Edmonds et al (1997), and Edmonds et al (1996).

A new hydrogen production sector and fuel cell technology component have been added to MiniCAM in order to carry out this analysis. Hydrogen in MiniCAM can now be produced from oil, gas, coal, biomass, or electrolysis. Carbon capture in hydrogen production is explicitly represented, and carbon is captured if economics are favorable or if policy mandates it.

At present, fuel cells generally take in methane and convert it to hydrogen only as an intermediate step in the production of electricity. The sectoral distinction in the MiniCAM model (i.e., treating hydrogen production as its own separate sector) may hence be somewhat artificial for some applications. However, for the purposes of investigating carbon emissions policy, it is necessary to have hydrogen production separate so that carbon capture technologies may be considered.

In the present analysis, fuel cells have been added to the electricity production sector and compete economically against the other technologies in MiniCAM, including fossil fuels, nuclear, solar, and hydroelectric. A potential blurring of the sectors exists in the special cases of cogeneration in industry and buildings, because in those cases electricity production is not exclusively limited to the utility sector. Hydrogen production in the model is indifferent as to whether it is produced at the site of use or some other location; hence, this analysis implicitly assumes that the transport of hydrogen can eventually be achieved at costs that are comparable for the transport of methane.

We developed three qualitatively different future energy and greenhouse gas emissions scenarios for this analysis for comparison against the MiniCAM's reference case scenario (hereafter referred to as BASE), which is adapted from the IPCC IS92a scenario (Edmonds et al 1994). The first of the constructed scenarios (referred to as FUELCELL) is an energy future where fuel cells are allowed to diffuse into the market place based solely on their relative performance characteristics subject to the energy prices and availability of energy resources present in the BASE case. The second constructed scenario (BIOMASS) differs from FUELCELL in that we now also assume that biomass for hydrogen production is cheap, abundant, and distributed throughout the world. The third scenario (SEQUEST) further extends this situation by requiring that all hydrogen production from carbonaceous feedstocks must sequester the carbon released during the transformation process.

We selected these scenarios in order to focus on the ability of fuel cells to contribute to reducing carbon emissions, the sole intent of this paper. While recognizing that fuel cells might offer other potential benefits to the economy and the environment, such as reductions in urban air pollution (which may even drive their use in some cases), we have not attempted to undertake an assessment of fuel cells' ability to contribute to these other energy and environmental policy goals. Table 1 summarizes the performance characteristics of fuel cells and hydrogen production technologies as input to MiniCAM.

Table 1: Assumed Performance of Various Hydrogen Production Methods

	Energy Input/Output Ratio	Levelized Cost for O&M and capital ($/GJ H_2 produced)
Coal (a)	1.292	4.66
Natural Gas (a)	1.115	1.72
Oil (b)	1.2	3.0
Biomass (a)	1.3	4.44
Electrolysis (a)	1.1	2.36

Sources: (a) Williams (1995) and (b) Kaarstad and Audus, 1997.

At the level of aggregation of energy services in the model's end-use sectors, it is perhaps most meaningful to present fuel cell technological performance assumptions stated relative to conventional combustion technologies. For fuel cell applications in MiniCAM's electricity production sector, we assumed that the electrical efficiencies of fuel cells start around 40% and increase to 66% over the next 30-40 years (FEMP, 1995), so that their cost of producing electricity is comparable to advanced gas turbines. For transportation, we assumed that fuel cells offered energy efficiencies 2.5 times greater than internal combustion engines with capital costs 25% higher (Thomas et al, 1997). For applications in industry, we assumed that fuel cells would compete directly with combustion cogeneration technologies, offering overall operational efficiencies of 80-85%. In buildings, fuel cells compete directly with purchased electricity at the efficiencies stated above for the electricity production sector. In each application, the final cost of using fuel cells depends on the price of hydrogen at each period, which is computed internally in the model.

In the BASE case, we assume that biomass can be grown on energy farms at an average productivity of 6 metric tonnes per hectare, with productivity increasing at 0.5%/year over the next century (Edmonds et al 1994). In the BIOMASS and SEQUEST cases, we assume that biomass can be grown at a productivity of 12 metric tonnes per hectare by the year 2020, with technical improvements of 0.5%/year thereafter.

Our assumptions about the cost and performance of carbon capture and sequestration technologies and how these technologies improve over time are summarized in Table 2.

ANALYSIS AND DISCUSSION OF RESULTS

We begin our discussion of results from this modeling effort by examining the production of hydrogen over the time period 1990-2095 in the three constructed scenarios. We then look at how this hydrogen is used by fuel cells in various sectors of the economy and the resulting impacts of the three scenarios on future carbon emissions.

Table 2. Assumed Cost and Performance of Carbon Capture and Disposal

	Coal	**Oil and Gas**
Energy Penalty for Carbon Capture [(a)]	37% declining to 9%	24% declining to 10%
Additional Investment Costs for Capture System [(b)]	54%	54%
Transport and Disposal Cost [(c)]	$15/tonne of C	$15/tonne of C
Efficiency of Capture [(b)]	90%	90%

Sources: (a) Herzog, et. al. 1997, (b) values are averages taken from Gottlicher and Pruschek (1997) survey of over 300 carbon capture technologies, (c) intermediate values from Freund and Ormerod, 1997.

Hydrogen Production

Respectively, Figures 1 (FUELCELL), 2 (BIOMASS), and 3 (SEQUEST) show primary hydrogen production for the three constructed scenarios.

Aggregate hydrogen production (i.e., hydrogen production from all sources) for each scenario exhibits the same basic pattern. A substantial jump in production occurs between 2005 and 2035 as hydrogen and fuel cell technologies begin to extensively penetrate the market, followed by a period of steady increase throughout the end of the next century. Total hydrogen production reaches its maximum of 444 exajoules (EJ) for the FUELCELL case, 486 EJ for the BIOMASS case, and 449 EJ in SEQUEST. As expected, the introduction of cheap, abundant and widely distributed biomass increases (by as much as 10%) hydrogen production for each time step (i.e., BIOMASS > FUELCELL). On the other hand, the introduction of the carbon sequestration requirement depresses total hydrogen production (i.e., BIOMASS > SEQUEST). This is because the requirement to sequester carbon in SEQUEST slightly increases the cost of hydrogen, making other energy services more competitive and offsetting some of the hydrogen production that is attributable to the cheap biomass assumption.

As noted earlier, methane is currently the primary feedstock for hydrogen production. Our modeling suggests that it will remain the dominant source of hydrogen production until well into the first half of the next century. However, in all three scenarios an important transition ultimately occurs: the primary source of hydrogen production switches from methane to biomass. The fact that it occurs in all three scenarios means that it is independent of the cheap biomass assumption (although lowering the price of biomass does accelerate the transition). This transition takes place because the price of natural gas rises over this period as the easily extractable, cheap resources are exhausted. Biomass continues to capture a larger market share until eventually becoming dominant.

Based upon the best data available to us, hydrogen production from oil and electrolysis appear unlikely to ever become major contributors unless fundamental breakthroughs are achieved that significantly reduce their respective costs. Coal, in contrast, could account for as much as 10% of hydrogen production, although we believe this unlikely given the external environmental considerations associated with producing and using coal. Accounting for these environmental externalities in the model (i.e., assigning them to all coal use) would likely result in even greater hydrogen production from methane and biomass.

Hydrogen Use

Although the numerical results differ among the three cases in the energy economy we have modeled, the overall patterns of hydrogen use do not. Therefore, in the interest of brevity, we show and discuss the results for the BIOMASS case only.

Because fuel cells blur the standard definitions of energy sectors, some clarification of our definitions is required. Specifically, the *Electricity* sector shown in the results below represents fuel cell applications in which the sole purpose is to produce electricity for sale. In the *Industry* and *Buildings* sectors, fuel cells produce electricity in addition to heat, with the electricity being produced primarily for own use but with any excess electricity sold to the grid. The *Transportation* sector consumes hydrogen simply to provide transportation services.

Figure 4 illustrates consumption of hydrogen in fuel cells for the BIOMASS case in each of these four sectors. From our MiniCAM model simulation, the electricity sector consumes the most hydrogen, in excess of 200 EJ/yr by the end of the next century. Industry consumes about 130 EJ/year by 2095, while transportation and buildings consume nearly 75 and 50 EJ/yr, respectively.

It is important to examine these consumption results on a relative basis to get a sense of scale. In Figure 5, we show these results expressed in terms of shares of sector totals. From Figure 5, hydrogen fuel cells capture between 25% and 30% of the electricity markets in each of the sectors by the middle of the next century. Shares decline slightly in later years as the sources of fuel for producing hydrogen (mainly methane and biomass in this case) become more expensive while technological improvements continue to be made in advanced electric generating technologies such as photovoltaics and nuclear power. We note cautiously, however, that these are simply modeling assumptions about technologies in the somewhat distant future. It is perhaps equally likely that hydrogen shares will grow as technologies for its production and consumption also improve.

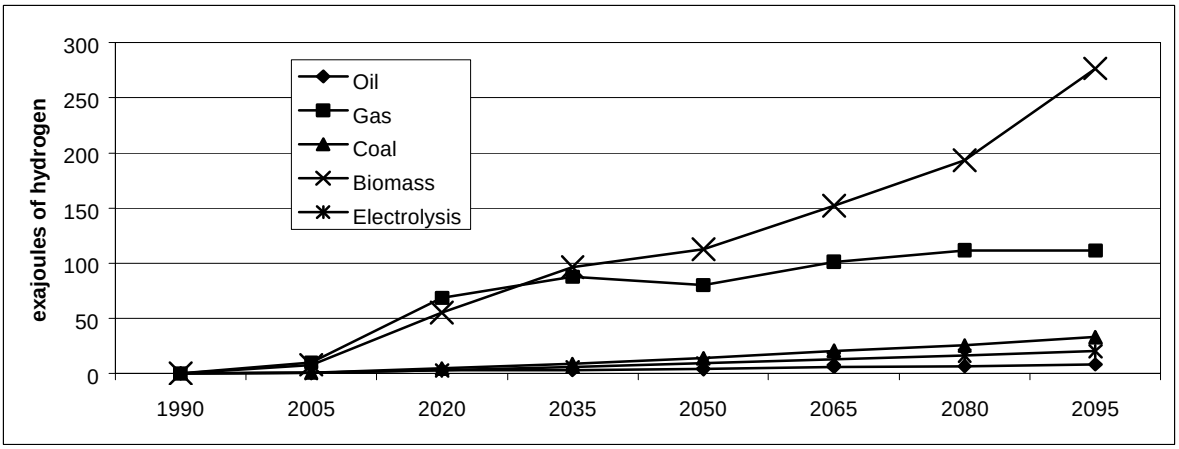

Figure 1: Global Hydrogen Production for the FUELCELL Case

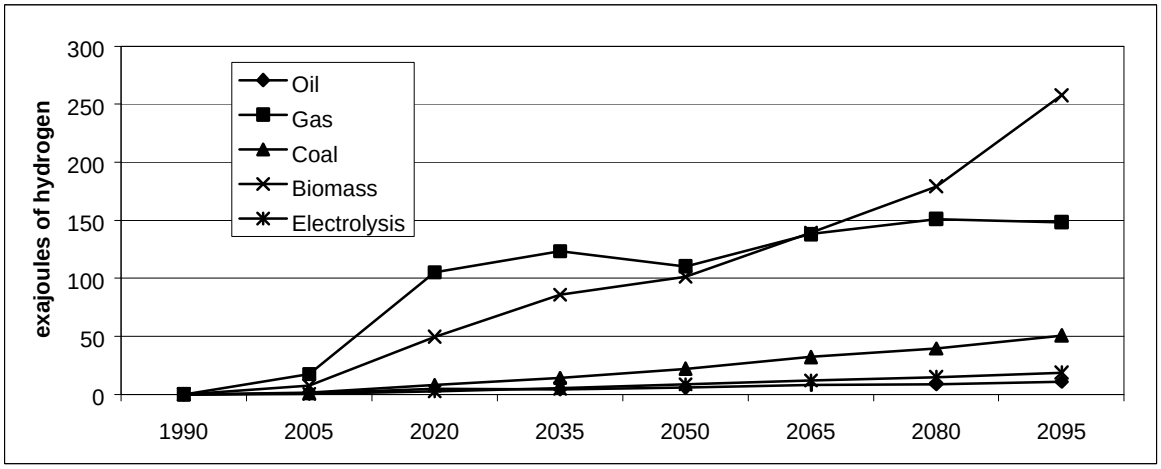

Figure 2: Global Hydrogen Production for BIOMASS Case

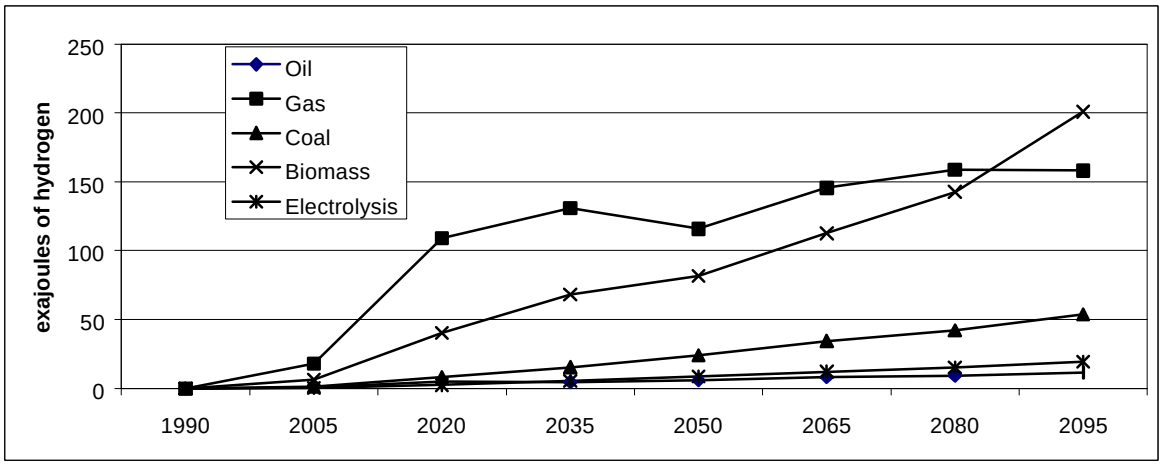

Figure 3: Global Hydrogen Production for SEQUEST Case

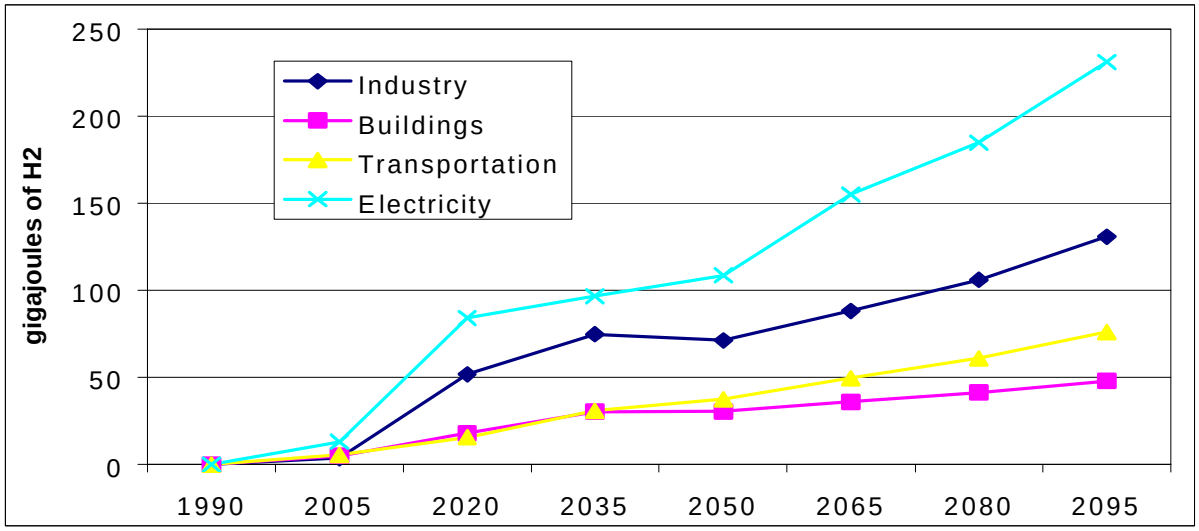

Figure 4: Global Hydrogen Consumption by Sector – BIOMASS

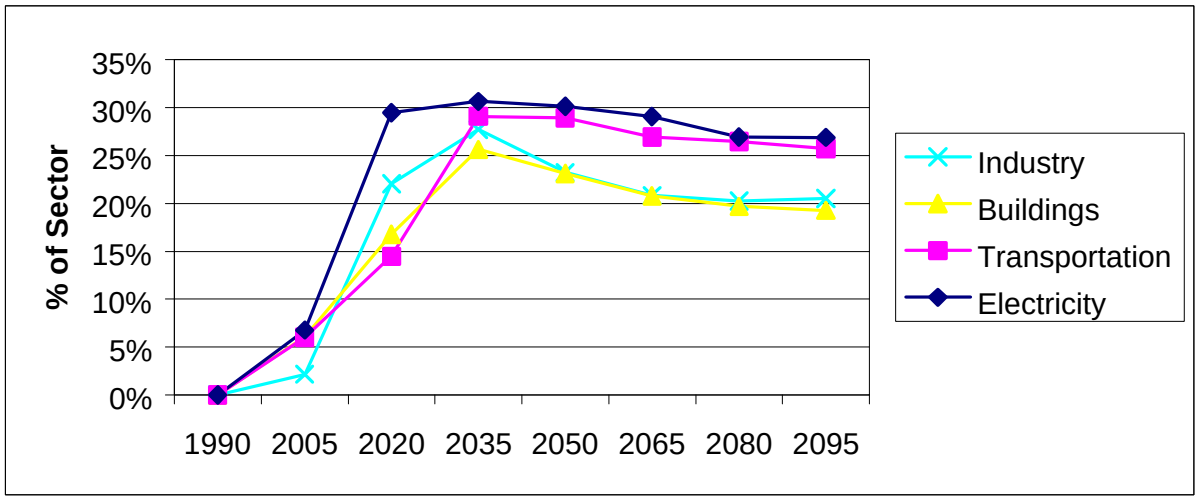

Figure 5: Hydrogen and Fuel Cells as Share of Total Global Energy Consumption by Sector

Carbon Emissions

Given our primary focus on the ability of fuel cells to contribute to reductions in carbon emissions, we conclude by examining annual emissions in the three scenarios. Figure 6 presents annual global carbon emissions for the three constructed cases and the BASE case.

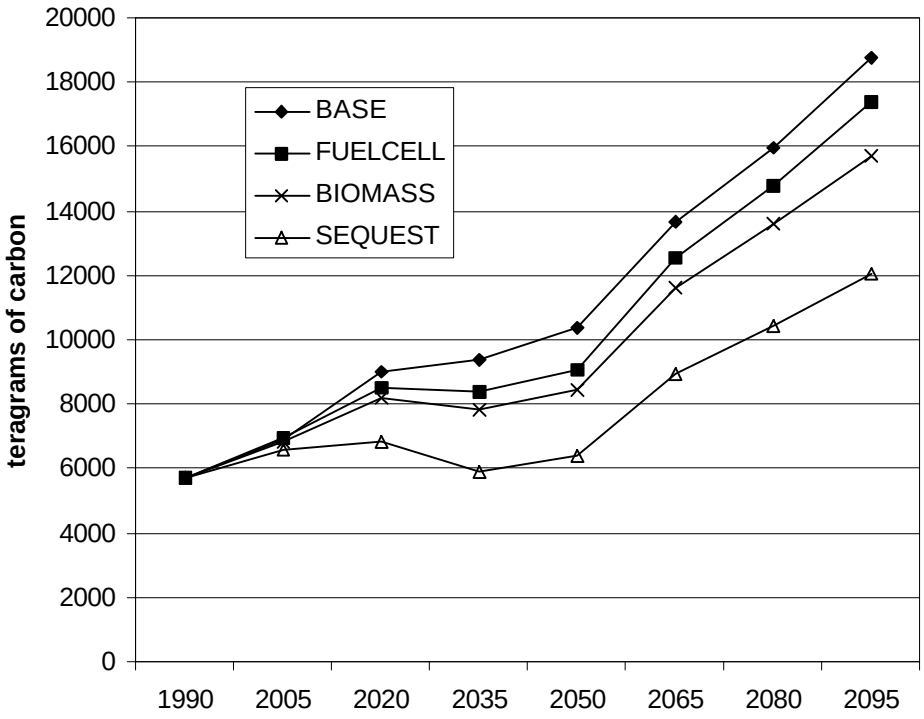

Figure 6. Global Annual Carbon Emissions

Fuel cells alone can make a modest but important contribution to reducing carbon emissions over the long term. The FUELCELL case reduces peak carbon emissions in the year 2095 by 7% when compared to the BASE case. The BIOMASS case (i.e., fuel cells in a world of abundant biomass) reduces the BASE case's peak emissions by 16% in the year 2095. Finally, the SEQUEST case (fuel cells and abundant biomass coupled with carbon sequestration) reduces annual carbon emissions in the year 2095 by a very substantial 36% relative to the BASE case.

BOUNDARIES OF THE CURRENT ANALYSIS

Fuel cells are a "crossover" technology in that they are deployable across various sectors, and their impacts are thereby extremely complex in terms of modeling. For example, a potential future scenario is that fuel cells will find widespread application in the transportation sector as the generator of electric power for electric vehicles. However, vehicles typically spend most of their time idle (i.e., parked) and could also become future stationary sources of electric power if they were plugged into the grid while not in mobile use. There may be distinct advantages to such a system of "dynamic" generation that follows the load, i.e., from the residential sector where the fuel cell vehicles have provided power overnight to the commercial sector where they are used during the day. Such scenarios, while entirely plausible, involve extremely complex procedures in terms of modeling and have not yet been incorporated into the analysis.

Another relevant consideration is the potential use of hydrogen by non-fuel cell power sources in the economy. Hydrogen production costs might be more rapidly improved through economies of scale or technological improvement than this study has anticipated were hydrogen to move into widespread use, for example, in hydrogen gas turbines or even modified internal combustion engines.

Addressing these issues will be a focus of future efforts.

CONCLUSIONS

Estimating the impacts of fuel cells and an economic shift to hydrogen is a difficult exercise. Hydrogen presents new modeling challenges because it can be considered both a fuel and an energy carrier, and fuel cell applications further blur the boundary between energy producing and energy consuming sectors. The current analysis represents a first attempt to assess the carbon emission reduction potential of fuel cells. With better data and an improved understanding of how fuel cells are likely to be used in the future, the current analysis will be refined and updated.

Given the caveat above, it does appear that widespread deployment of fuel cells in an economy shifting from fossil fuels to hydrogen will achieve significant reductions in future carbon emissions, but there are some specific technological improvements required before this can occur. Necessary avenues of future research appear to be efforts designed to speed the introduction of large-scale biomass production and biomass-derived hydrogen generation. These areas are especially important in light of the transition that will have to take place during the next century from methane-derived to biomass-derived hydrogen. Other fossil fuel hydrogen production technologies, including conversion of coal and oil resources, while still possible, do not appear to be economically competitive for large-scale implementation and therefore seem less likely.

Ultimately, production of hydrogen through water electrolysis would cease to involve carbon in the energy cycle and would probably be most preferable from an environmental standpoint. Sufficient economic development of this technology would eliminate corresponding global warming and other environmental concerns, however the necessary cost reductions from the present situation are quite large. Our analysis suggests that this will not occur due to the smaller effort required to make biomass-derived hydrogen economically competitive.

Finally, all of these improvements are in addition to the technological gains still required in the fuel cells themselves, already the focus of ongoing worldwide research.

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