Emissions in a Hydrogen Economy

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1. Introduction

In 2003, President George W. Bush announced a $1.2 billion hydrogen initiative to bring hydrogen-powered fuel cell vehicles from concept to the marketplace [1]. The proper motivation for this effort lies in the advantages of hydrogen fuel cells from an environmental perspective. Fuel cells are energy conversion devices that electrochemically combine hydrogen and oxygen to produce electricity with water vapor as the only byproduct. This is in sharp contrast to traditional thermal cycles (such as the internal combustion engine), which capture useful work from the heat released by combustion of fuel in air. Not only is the thermal cycle efficiency limited by the second law of thermodynamics, but the combustion process is never ideal, resulting in emissions of tropospheric ozone precursors including unburned fuel (hydrocarbons such as CO and VOCs), nitrogen oxides (NOx), and sulfur oxides (SOx). Additionally, combustion of carbon-based fuels releases the greenhouse gas, CO_2.

Considering that surface air quality is projected to be a major concern throughout the coming century [2], and that anthropogenic emissions of greenhouse gases are causing potentially dangerous climate perturbations [3], we are motivated to evaluate the proposed "hydrogen economy" as a potential solution to these problems. In this study, a baseline scenario for projected emissions of CO_2 and ozone precursor molecules during the years 1990 – 2100 is compared to a scenario in which the entire transportation sector is converted from petroleum fuel to hydrogen. Additionally, the possibility that the resources spent on the hydrogen economy infrastructure might be better invested (for example, replacing coal-powered electric plants with carbon-free electrical generation capacity) is investigated.

2. Business-As-Usual Emissions

In the Intergovernmental Panel on Climate Change (IPCC) assessment report, projected emissions for several broad socioeconomic pathways are cited. Here, the A1FI projections are used for the reference, business-as-usual (BAU) case. This case describes a world of rapid economic growth, global population peak near mid-century, and rapid introduction of new and more efficient technology. Energy sources remain fossil intensive throughout as seen in Figure 1 (left side). The values for total energy use and the portion assigned to coal power and carbon-free power are given explicitly in the assessment report. The proportion for transportation (~22%) is based on current usage and held approximately constant over the entire century.

2.1 Greenhouse Gases

Unfortunately, this scenario implies the production of large amounts of CO_2 that society must contend with (Figure 1, right side). The cumulative carbon emissions over the entire century are 2300 G t of C. If released to the atmosphere as CO_2, this would result in concentrations approaching 1000 ppm by century's end. The largest contributor to CO_2 emissions would be coal-power (29.3 MJ/kg) because it is the largest energy source and has a very high carbon content (>90% C by weight). Energy for the transportation sector comes primarily from gasoline and diesel (44 and 42 MJ/kg, respectively) which have somewhat lower carbon content (84% C by weight). The remaining fossil fuel used is assumed to be similar to natural gas (45 MJ/kg and 75% C by weight). In this simplified analysis, the transportation sector would not contribute to methane (CH_4) emissions and so this greenhouse gas is not considered.

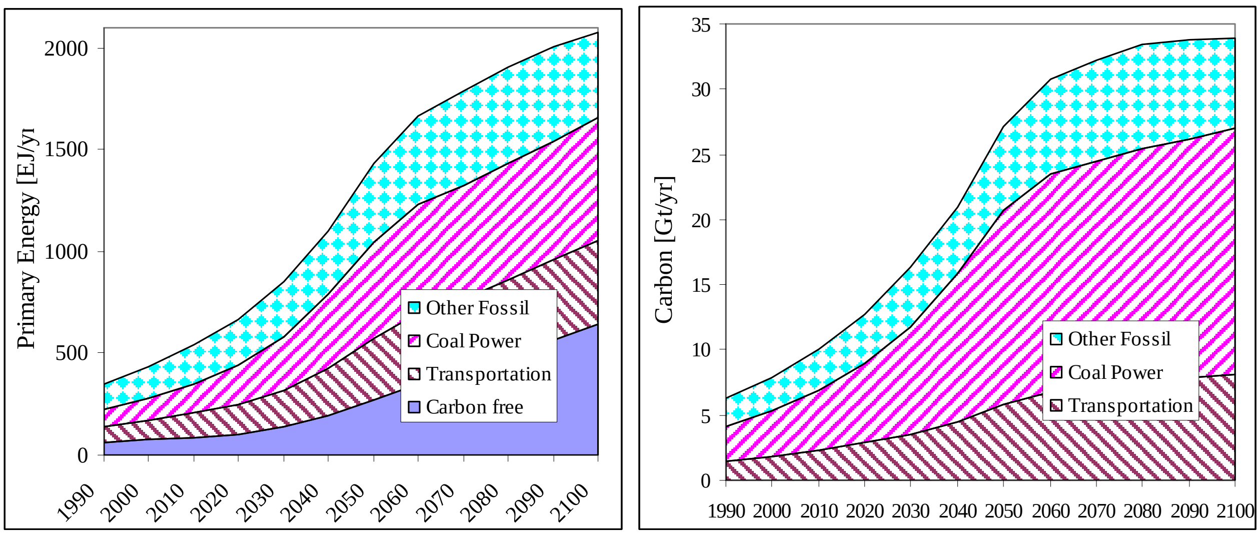

Figure 1. Projected global primary energy usage (EJ/yr) and resulting carbon emissions (Gt C/yr) for the period 1990 – 2100.

2.2 Tropospheric Ozone Precursors

Surface air quality, especially in and around urban areas is an important environmental concern. Vehicle exhaust emissions of CO, VOCs, NOx, and SOx are expected to increase significantly as gains from increased usage exceed reductions from stricter emissions controls. Table 1 lists the projected global anthropogenic emissions of these species [3] and the proportion of the emissions that comes from transportation and coal-power (based on U.S. data for 1996) [4]. The values for CO do not include biomass burning, which accounts for half of anthropogenic CO emissions. Additionally, current molecular hydrogen emissions from vehicle exhaust [8] are estimated to grow in proportion to growth of the transportation sector. Possible environmental concerns related to increased H_2 emissions are discussed later.

Table 1. Air Quality Emissions for the 21st Century

Year	**CO** (Mt CO/yr)	**VOC** (Mt/yr)	**NOx** (Mt N/yr)	**SOx** (Mt S/yr)	H_2 (Tg/yr)
1990	440	139	31	71	10
2020	602	192	50	87	20
2050	1080	322	95	81	42
2100	1285	420	110	40	61
Transportation	79%	41%	50%	3.5%	100%
Coal Power	4%	3%	23%	60%	0%

3. Hydrogen Economy Scenario

The current vehicle fleet and the infrastructure supporting it is based on liquid petroleum transportation fuels. In the hydrogen economy scenario, the entire sector will be fueled by hydrogen and all vehicles will be equipped with fuel cell power plants producing no emissions locally (except possibly from leakage of H_2). The hydrogen will be produced entirely from non-carbon sources and will thus require a simultaneous investment in additional solar, wind, nuclear, or other capacity (or carbon sequestration). This assumption is made in order to simplify the scenario and show the maximum possible benefit that could arise from the hydrogen economy.

An example scenario is as follows: in 2008, fully 1% of the petroleum based transportation sector is replaced with hydrogen. Then, the hydrogen sector grows at 50% annually, displacing more and more of the petroleum based sector. By 2020 then, the entire transportation sector would be hydrogen, and the growth rate would only need to keep up with new demand (which is the same as in the BAU scenario). This scenario would reduce the accumulated CO_2 emissions from the present – 2100 by approximately 21%. Unfortunately, the technology is not ready for commercialization and the growth rates of the necessary infrastructure are much too optimistic.

The President’s initiative calls for a “decision” to be made on hydrogen by 2015, and with a positive decision, mass-market penetration to begin by 2020. Following this guide, the hydrogen economy scenario is as follows: in 2020, fully 1% of the petroleum based transportation sector is replaced with hydrogen (through a Herculean effort). Then, the hydrogen sector grows at 25% annually, displacing more and more of the petroleum based sector. By 2043 then, the entire transportation sector would be hydrogen, and the growth rate would only need to keep up with new demand (which is the same as in the BAU scenario). This scenario would reduce the accumulated CO_2 emissions from the present – 2100 by approximately 18% as seen in Figure 2.

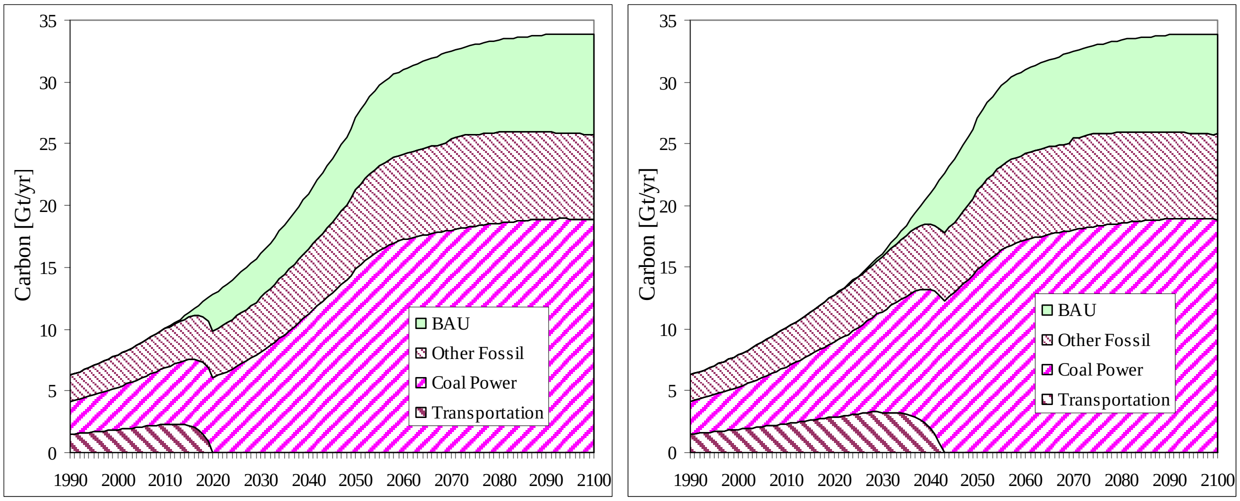

Figure 2. In an unlikely scenario, carbon-free hydrogen immediately begins to replace petroleum in the transportation sector (left) leading to immediate reductions in CO_2 emissions. In a more reasonable scenario, implementation begins in 2020 (right) and is complete by 2043.

3.1 Molecular Hydrogen Emissions

With such widespread penetration of hydrogen as a transportation fuel, there is likely to be significant emissions due to leakage or other loss. Tromp, et al. [5] studied the effects of increased hydrogen on the stratosphere and found that a multiple-fold increase would lead to measurable temperature drop in the lower stratosphere and thus a depletion of ozone. Schultz, et. al. [6] recognized that tropospheric H_2 acts as an ozone precursor in a similar fashion to CO. The total atmospheric burden of H_2 is 175 Tg, or 0.5 ppm [7]. Estimated total emissions are 70-90 Tg/yr with approximately 5-25 Tg/yr from anthropogenic sources [8]. The total atmospheric lifetime is 1.4 – 2 years [9, 10] with as much as 80% of tropospheric H_2 taken up by soils, and the remainder photochemically oxidized. It is unclear how the sources and sinks of stratospheric and tropospheric H_2 would be affected by increases in anthropogenic H_2 emissions.

In the hydrogen economy scenario, hydrogen (120 MJ/kg) completely replaces petroleum in the transportation sector. Assuming 3% [8] of the hydrogen is lost to the atmosphere, the projected emissions of hydrogen are shown in Figure 3. Assuming an atmospheric lifetime of 2 years, the corresponding hydrogen concentration is also shown in the figure. A doubling of atmospheric H_2 by century's end is therefore reasonable to expect. All else being equal, this would have the effect of increasing the lifetime of CH_4 (a potent greenhouse gas) by 20%, increasing tropospheric ozone [6], and decreasing stratospheric ozone by less than 2% [5]. Of course, higher leakage is possible but not likely due to economic and practical concerns. Reductions in other surface air quality emissions will more than make up for the increased H_2 emissions as illustrated in the next section.

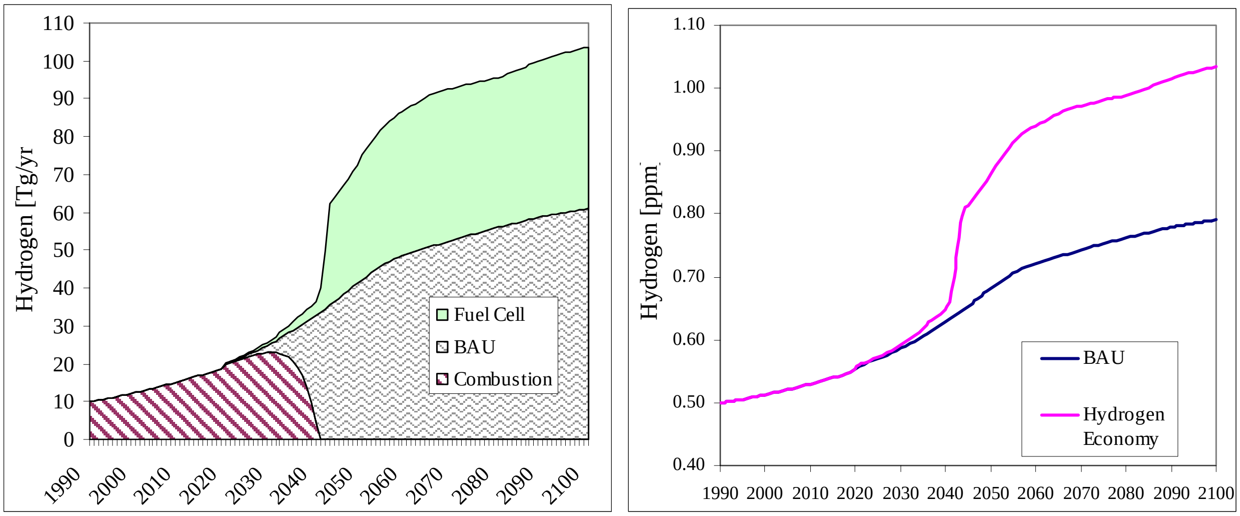

Figure 3. Hydrogen emissions (left) projections and the corresponding increasing in atmospheric hydrogen concentration (right) for the coming century.

3.2 Tropospheric Ozone Precursors

Because the fuel cell vehicles do not produce any pollution, and the hydrogen is produced without causing any emissions, the entire transportation sector emissions (excluding H_2) would be zero in the hydrogen economy scenario. The projected reductions in ozone precursor species given in Table 1, are shown in Figures 4 and 5. Carbon monoxide (CO), volatile organic compounds (VOCs), and nitrogen oxides (NOx) all are reduced dramatically. Sulfur dioxide (SOx) is only reduced by a negligible amount because transportation only accounts for 3.5% of total emissions. The reductions projected will have a significant impact on air quality in urban areas with a high density of vehicular traffic. More detailed modeling including all chemical reaction pathways, atmospheric transport, non-anthropogenic emissions, and seasonality, is necessary to quantify regional effects on surface ozone and air quality.

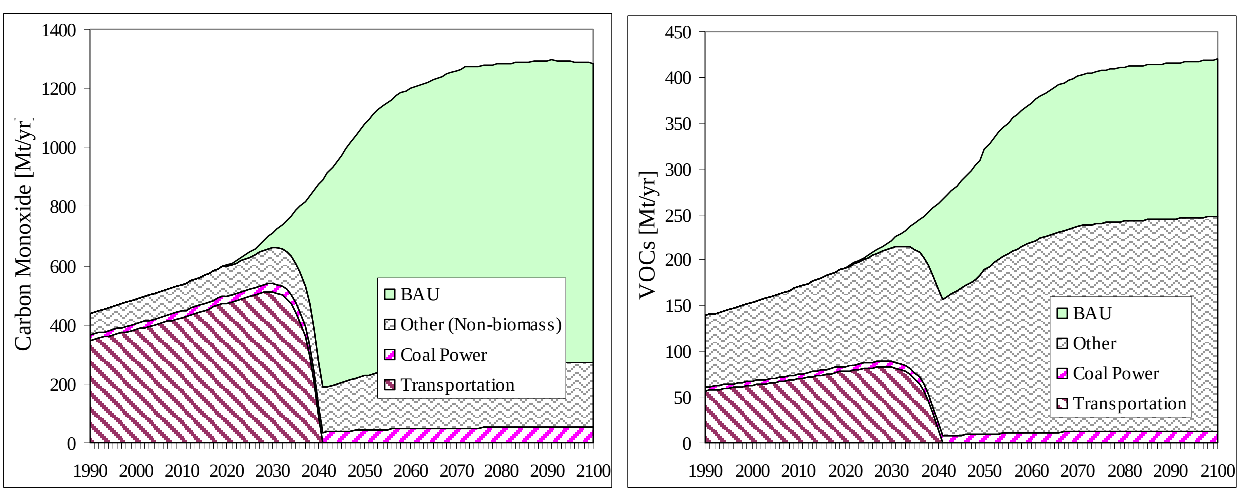

Figure 4. Projected emissions of carbon monoxide (Mt/yr) and VOCs (Mt/yr) comparing business as usual (BAU) to the hydrogen economy scenario.

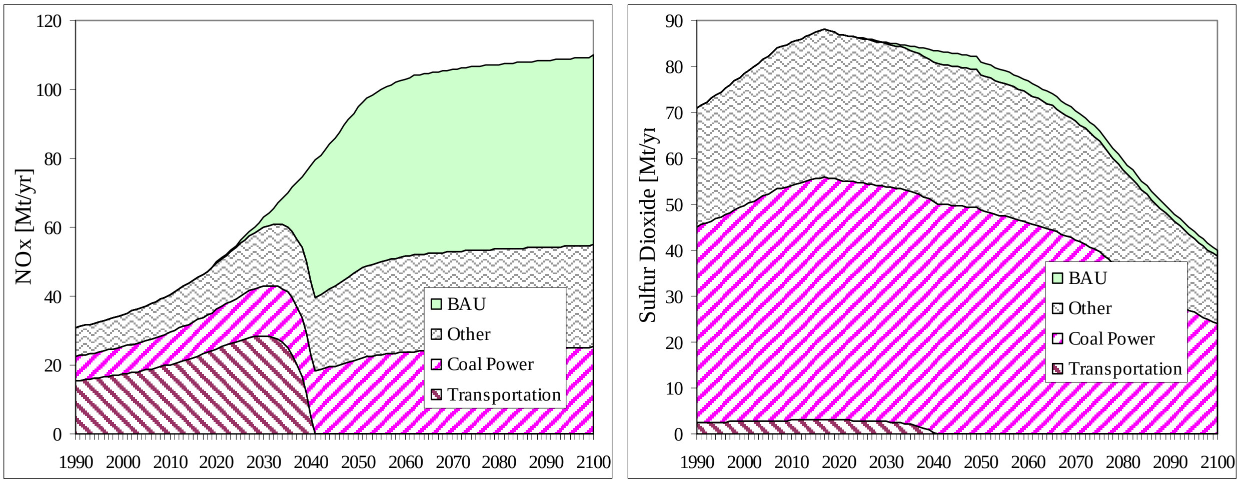

Figure 5. Projected emissions of nitrogen oxides (Mt/yr) and sulfur dioxide (Mt/yr) comparing business as usual (BAU) to the hydrogen economy scenario.

4. Discussion

Business as usual emissions of both CO_2 and surface air quality species are expected to grow to dangerous levels. The hydrogen economy can provide a 20% reduction in CO_2 emissions if hydrogen is produced from carbon free sources. Ozone precursor molecules can be reduced significantly, especially in urban areas if the hydrogen economy completely displaces petroleum fueled vehicles. Emissions of sulfur dioxide would not be affected significantly, however.

The envisioned hydrogen economy requires a substantial investment in fuel cell development and production, hydrogen production, distribution and storage, and a carbon-free energy source of equal magnitude to the transportation energy sector's needs. Such a large source of carbon-free energy could be used to displace coal powered electric plants instead. This would avoid more carbon emissions than the hydrogen economy because coal has a higher carbon density than petroleum fuel. Additionally, SO_2 emissions would be reduced substantially. On the other hand the reductions in CO and VOCs would be negligible compared to the hydrogen economy scenario.

A hydrogen economy can play a role in addressing the problems of unmitigated greenhouse gas emissions and deteriorated surface air quality in the coming century. While it may pose its own environmental threats, on balance it appears to be a net positive for the environment. It is not a silver bullet, and is only an incremental part of the total solution to our energy and environment needs.

References

[1] U.S. Dept. of Energy; http://www.energy.gov/energysources/hydrogen.htm.
[2] Prather M, Gauss M, Berntsen T, Isaksen I, Sundet J, Bey I et al. Fresh air in the 21st century? Geophysical Research Letters 2003;30(2):-.
[3] Intergovernmental Panel on Climate Change Assessment Report, Climate Change 2001.
[4] Tester JW, Drake EM, Driscoll MJ, Golay MW, Peters WA. Sustainable Energy: Choosing among options. Cambridge, MA: MIT Press; 2005.
[5] Tromp TK, Shia RL, Allen M, Eiler JM, Yung YL. Potential environmental impact of a hydrogen economy on the stratosphere. Science 2003;300(5626):1740-2.
[6] Schultz MG, Diehl T, Brasseur GP, Zittel W. Air pollution and climate-forcing impacts of a global hydrogen economy. Science 2003;302(5645):624-7.
[7] Rohs S, Schiller C, Riese M, Engel A, Schmidt U, Wetter T et al. Long-term changes of methane and hydrogen in the stratosphere in the period 1978-2003 and their impact on the abundance of stratospheric water vapor. Journal of Geophysical Research-Atmospheres 2006;111(D14):-.
[8] Prather MJ. An environmental experiment with H-2? Science 2003;302(5645):581-2.
[9] Rahn T, Eiler JM, Boering KA, Wennberg PO, McCarthy MC, Tyler S et al. Extreme deuterium enrichment in stratospheric hydrogen and the global atmospheric budget of H-2. Nature 2003;424(6951):918-21.
[10] Rhee TS, Brenninkmeijer CAM, Rockmann T. The overwhelming role of soils in the global atmospheric hydrogen cycle. Atmospheric Chemistry and Physics 2006;6:1611-25.