Hydrogen as a future energy source. An impact study

Violeta-Carolina Niculescu, Mihai Anghel, Ioan Stefanescu

Abstract—One of the major impediments for the transition to a hydrogen based energy system is the lack of satisfactory hydrogen storage alternatives. In a future sustainable energy system based on renewable energy, environmentally harmless energy carriers like hydrogen, will be of crucial importance. Hydrogen is an important, though little studied, trace component of the atmosphere. It exists at the mixing ratio of about 510 ppb. Hydrogen is an indirect greenhouse gas with a global warming potential GWP of 5.8 over a 100-year time horizon. A future hydrogen economy would therefore have greenhouse consequences and would not be free from climate perturbations. Our study focuses on the environmental impact of using hydrogen as a energy source. If a global hydrogen economy replaced the current fossil fuel-based energy system and exhibited a leakage rate of 1%, then it would produce a climate impact of 0.6% of the current fossil fuel based system.

Keywords— atmosphere, greenhouse effect, environment hydrogen economy, impact.

I. INTRODUCTION

In past decades, efforts to harness renewable energies were driven partly by idealism but more by concerns about “energy security”—fears about the eventual drying up of the world’s petroleum resources and about the increasing vulnerability of the long supply lines from the politically unstable Middle East [1].

But as the twentieth century drew to its close, environmental concern had become a much stronger impetus driving the world toward renewable, alternative forms of energy.

Curbing and eventually doing away with pollution has become a universal concern. Dying forests in Europe and acid rain everywhere were among the initial wake-up calls to the need to curb sulfur, nitrogen oxides, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), particulate emissions, and other pollutants.

At last it had begun to dawn on policy makers and large parts of the general population—less so, and more slowly, in the United States than in other parts of the world—that the very process of combusting fossil fuels, the interaction of carbon in hydrocarbon fuels with the air’s oxygen, and the consequent release into and accumulation in the atmosphere of carbon dioxide, carbon monoxide, and other climate-changing gases far above preindustrial levels was raising the world’s temperature—the famous Greenhouse Effect—and threatening to play havoc with the world’s climate.

“Zero emissions” from cars and buses, industry, ships, and home furnaces is becoming the new world standard—a standard to which industrialized countries and emerging economies are aspiring with varying degrees of intensity and dedication.

To the minds of many, taking the carbon out of hydrocarbons and relying on the “hydro” part—hydrogen—as a zero emission chemical fuel is the obvious though technically difficult way to minimize and, it is hoped, eventually eliminate global warming.

The basics of global warming are as follows: Carbon dioxide (CO_2) is produced by the burning of fossil fuels as well as by nature’s carbon cycle. (Humans and animals exhale it into the atmosphere as part of their metabolic process; green plants absorb it and turn it into plant matter.) CO_2, methane, and other gases act like a greenhouse in the atmosphere: they let solar radiation through the atmosphere to heat the Earth’s surface, but they prevent the re-radiation of some of that energy back into space, thus trapping heat [2].

Some heat entrapment is good; otherwise we would have never evolved in the first place, or we would freeze to death. But the more greenhouse gases are swirling around the atmosphere, the more heat is trapped.

Because of decreases in the world’s forests and consequent decreases in global CO_2 absorption, and (more important) because of increasing burning of fossil fuels in our ever-more-energy-demanding machinery, the atmosphere’s CO_2 content has been going up steadily and increasingly steeply since the beginning of the Industrial Revolution.

Aside from other fundamental climate cycles stretching over thousands or tens of thousands of years (such as ice ages, believed to be caused in parts by changes in sunspots and therefore beyond man’s ability to influence), Earth’s climate has been reasonably stable for 10,000 years or so. But this

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equilibrium is being upset by man-made carbon emissions. The question is how much.

Opinions, basic assumptions about the future course of the climate and the amount of expected heat increase, closely related assumptions about global economic development, and faith in the complex computer models that attempt to forecast climate developments vary widely even among the majority of experts who believe that our planet is facing an unprecedented crisis.

As more heat is being trapped, and as temperatures climb all over the world, the mainstream opinion among the climate experts of the United Nations' Intergovernmental Panel on Climate Change (IPCC) predicts widespread and drastic impacts on ecosystems, water resources, food and fiber production, coastlines, and human health: the polar ice caps will melt, sea levels will rise, large stretches of coastline (including some of the world's biggest cities) will be inundated, and scores of islands in the Pacific may disappear [3].

Agricultural patterns are likely to change, with grain-growing belts migrating northward. The middle to high latitudes may become more productive as plants absorb more available CO_2. The agricultural yields of the tropics and the subtropics are expected to decrease.

Climate change could produce more deaths through heat stress, the spread of tropical diseases, and worse urban air pollution. In a special supplement dedicated to the December 1997 *Global Climate Change Conference* in Kyoto, the *New York Times* reported that one IPCC working group had summarized its findings as follows: "Compared with the total burden of ill health, these problems are not likely to be large.

It is safe to say that, in general, we work and play with—and, environmentalists would say, more frequently than ever die from—fossil-fuelled chemical energy.

Gasoline, diesel fuel, heavy oil, jet-grade kerosene, natural gas, wood, biomass, and coal propel airplanes, cars, trains and ships, run plants, and heat homes, offices, hospitals, and schools. Hydrogen, also a form of chemical energy, can do all those things, and can do them essentially without polluting.

When burned in an internal-combustion engine (piston, rotary, or gas turbine), hydrogen produces as exhaust virtually nothing but harmless water vapour (plus, admittedly, trace emissions from tiny amounts of engine lubricants that are oxidized in the process, and some nitrogen oxides).

When hydrogen is combusted with atmospheric oxygen in an engine, no carbon monoxide or carbon dioxide is emitted, no unburned hydrocarbons, no stench, no smoke, nor any of the other carbon-bearing, Earth-befouling discharges we suffer today.

Hydrogen performs even better in fuel cells (electrochemical engines that, by electrochemically combining hydrogen and oxygen in a flameless process, produce electricity, heat, and pure, distilled water—the mirror image of electrolysis, in which water is split into hydrogen and oxygen by running a current through it).

Unlike internal-combustion engines, fuel cells produce no nitrogen oxides at all. Fuel cells have no moving parts. Nearly silent, they can be as much as 2.5 times as efficient as internal-combustion engines.

In the 1990`s they became widely and publicly recognized as a vanguard technology that may launch hydrogen energy on its way to becoming a major, environmentally benign, sustainable, renewable component of the world's energy mix for both transportation and stationary applications.

Hydrogen, H_2, atomic weight 1.00797 is the lightest known substance, reports the *Encyclopedia of Chemistry*. The spectroscope shows that it is present in the sun, many stars, and nebulae.

Our galaxy plus the stars of the Milky Way is presently considered to have been formed 12 to 15 billion years ago from a rotating mass of hydrogen gas which condensed into stars under gravitational forces. This condensation produced high temperatures, giving rise to the fusion reaction converting hydrogen into helium, as presently occurring in the sun, with the evolution of tremendous amounts of radiant thermal energy plus the formation of the heavier elements [4].

Hydrogen gas has long since escaped from the Earth's lower atmosphere but is still present in the atmosphere of several of the planets. In a combined state, hydrogen comprises 11.19 percent of water and is an essential constituent of all acids, hydrocarbons, and vegetable and animal matter. It is present in most organic compounds.

Hydrogen seems to have low impact on the environment, but there are a number of uncertainties concerning the consequences of a large-scale shift towards a hydrogen economy.

Hydrogen is forecast to become a major source of energy in the future, thus offering a potentially non-polluting, inexhaustible, efficient, and cost-attractive energy carrier [5]. In the last 10 years, the defining issues with respect to H_2 economics have changed dramatically. However, refineries now have become net consumers of H_2 in an effort to reduce pollution and meet environmental regulations.

Hydrogen can be produced from a variety of feed stocks; from fossil resources such as natural gas and coal, and from renewable resources such as biomass and water with input from renewable energy sources (e.g. sunlight, wind, wave or hydro-power) [6], [7].

Local availability of feedstock, maturity of technology, market applications and demand, policy issues and costs will influence the choice and timing of the various options for hydrogen production. An overview of the various feed stocks and process technologies is presented in Fig. 1.a [8] [9]:

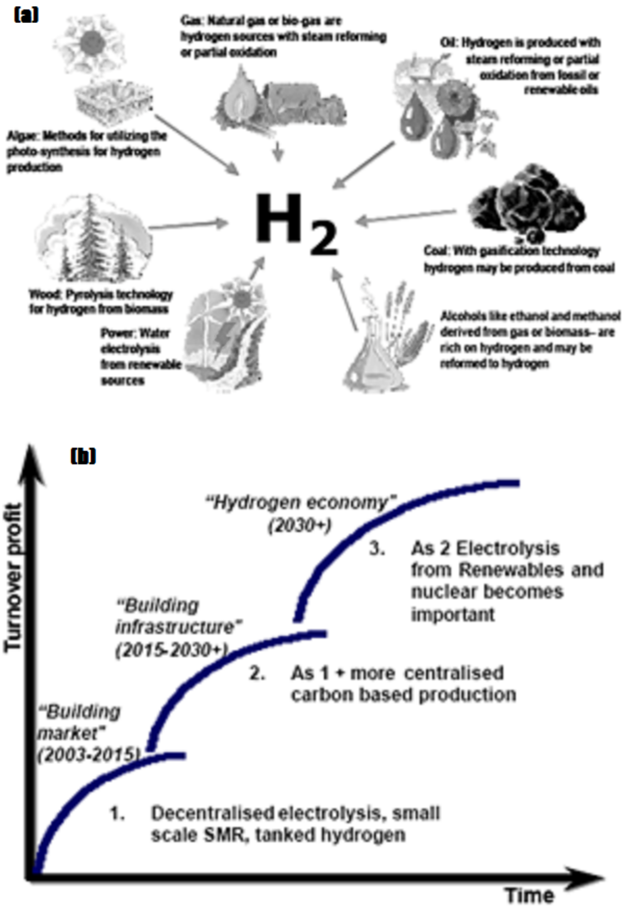

Fig. 1 Some feedstock, process alternatives (a) and main hydrogen pathways (b)

In Fig. 1.b a future hydrogen pathway is illustrated. Large-scale hydrogen production is probable on the longer time scale. In the current and medium term the production options for hydrogen are first based on distributed hydrogen production from electrolysis of water and reforming of natural gas and coal. Larger centralized hydrogen production plants are more likely to be introduced at a later stage. These plants will probably be based on biomass or fossil fuels with CO_2-capture and storage.

Scientists, engineers, industry and policy makers think that there are two ways to make a vehicle run on hydrogen: by using the hydrogen in an internal combustion engine or by using the hydrogen in a fuel cell.

Hydrogen economy needs to solve the challenging problems involved with the synthesis of hydrogen, its storage, distribution and utilization in all of the sectors of the energy economy, transport included. But, first of all, it must be very good understand the fate and behaviour of hydrogen in the atmosphere and its major sources and sinks. Hydrogen itself, in contrast to most expectations, is a greenhouse gas and can be quantified by its global warming potential relative to carbon dioxide.

TABLE I
GLOBAL SOURCES AND SINKS FOR HYDROGEN

Sources and sinks (Tg per year) [a]	[12]	[9]	[13]
Sources			
Methane oxidation	15.0	26.0	15.2
NMHC [b]	25.0	14.0	15.0
Biomass burning	20.0	16.0	20.0
Anthropogenic [c]	20.0	15.0	20.0
Nitrogen fixation	3.0	3.0	4.0
Oceans	4.0	3.0	4.0
Total sources	87.0	77.0	78.2
Sinks			
OH-oxidation	8.0	19.0	17.1
Soil uptake	90.0	56.0	58.3
Total sinks	98.0	75.0	74.4

[a] Tg = 10^{12} g
[b] Non-methane hydrocarbons
[c] Hydrogen from fuel combustion

II. POTENTIAL IMPACT OF HYDROGEN ON ATMOSPHERE

Hydrogen is one of the major trace gases in the lower atmosphere or troposphere. The global mixing ratio of hydrogen is currently about 510 ppb, 500 ppb in the northern hemisphere and 520 ppb in the southern hemisphere [10]. Although its life cycle has been heavily influenced by human activities, its mixing ratios in the northern hemisphere are lower than those in the southern hemisphere, hydrogen being unusual among trace gases. This is caused by the main sink for hydrogen, surface uptake by soils, which accounts for 80% of the total loss of hydrogen from the atmosphere. The majority of the sink is therefore occurring over the continental land masses in the northern hemisphere.

Recent analyses of long-term observations of hydrogen in the troposphere indicate that mixing ratios have remained fairly constant during the last decade [11].

The (incomplete) combustion of fossil fuel and biomass in boilers and internal combustion engines generates hydrogen along with carbon monoxide and carbon dioxide. This source represents about 40% of all the hydrogen released into the atmosphere. Another important source, accounting for an estimated 50% of atmospheric hydrogen emissions, is the atmospheric photochemical oxidation of methane (CH_4) and non-methane hydrocarbons (NMHCs). Emissions from volcanoes, oceans and nitrogen-fixing legumes account for the remaining 10% [12], [13]. Movement of hydrogen into the upper atmosphere and then to space is negligible in terms of the global hydrogen budget. Instead, hydrogen is removed from the atmosphere largely through dry deposition at the surface and subsequent microbiological uptake in soils. The rate of uptake depends on microbial activity, soil texture and moisture content. This sink is largest in the northern hemisphere because of its larger landmass.

The first analysis [14] estimated a global production rate of 23.9 Tg per year, largely from human activities and a global sink strength of 17.5 Tg per year, due to the reaction below:

$$OH + H_2 = H + H_2O \tag{1}$$

In order to estimate the production of hydrogen from methane, through the photolysis of formaldehyde HCHO, a global box model has been used [15]:

$$OH + CH_4 = CH_3 + H_2O \tag{2}$$

$$CH_3 + O_2 = CH_3O_2 + M \tag{3}$$

$$CH_3O_2 + NO = CH_3O + NO_2 \tag{4}$$

$$CH_3O +_2 O = HO_2 + HCHO \tag{5}$$

$$HCHO + h\nu = H_2 + CO \tag{6}$$

The uptake of hydrogen by soils [14] is known like an additional sink for hydrogen. Also, global hydrogen budgets have been based on the oxidation rates of the primary emitted hydrocarbons and removal by OH-oxidation and uptake by soils [13], [16], [17] – see table 1.

For the representation of various sources and sinks of hydrogen in troposphere, it was used a 3D chemistry transport model STOCHEM [17].

Regarding man-made sources, these include fossil fuel combustion, mainly from motor vehicles with petrol, through the water gas reaction:

$$CO + H_2O = H_2 + CO_2 \tag{7}$$

Another source of hydrogen in troposphere is the biomass burning (incomplete combustion). Also, the surface ocean waters are generally supersaturated with hydrogen and so act as a small source [14]. Hydrogen is also formed as a by-product of nitrogen fixation in leguminous plants [18].

The modelling study using STOCHEM [13] shows that the OH-oxidation of methane produces 15.2 Tg per year of hydrogen and that of isoprene, 11.0 Tg per year and other organic compounds account for a further 4.1 Tg per year.

The main chemical sink for hydrogen in the troposphere is the reaction with hydroxyl radicals - see reaction (1). The largest source of hydroxyl radicals is the reaction of electronically excited oxygen atoms O^1D from the photolysis of ozone O_3, with water vapour H_2O:

$$O_3 + h\nu = O^1D + O_2 \tag{8}$$

$$O^1 + H_2O = OH + OH \tag{9}$$

Another major sink for hydrogen is uptake by soils at the earth's surface, the rates depending on the nature of the soils, the properties of each trace gas and the transport of the trace gas through the atmospheric boundary layer by turbulence to the earth's surface.

All these atmosphere reactions, closely linked one each other, determine the capacity of the atmosphere to neutralise pollutants.

Field studies (Table 1) have indicated a dependence of the soil uptake of hydrogen on soil moisture content and on the ecosystem type growing on the soil [19]–[21]. Soil uptake rates, expressed as dry deposition velocities, range from 1.3 mm s^{-1} for savannah systems to 0.1 mm s^{-1} for semi-desert systems. For an observed global hydrogen burden of 182 Tg [10], the global sink strength of 74.4 Tg per year, implies an atmospheric lifetime of 2.5 years or thereabouts for hydrogen [17].

Usually, the measured concentration of hydrogen in troposphere (the part of the atmosphere extending from the earth`s surface up to about 17 km) is 0.5 ppm and the measured concentration in stratosphere (17-50 km altitude) is 0.4-0.5 ppm, but this concentration has an year cycle. For the northern hemisphere, the amplitude of variation is about 0.04-0.08 ppm and the southern one is about 0.02-0.04 ppm. These variations are due to the increased CH_4 and NMHC (non-methane hydrocarbons) values in the winter and high values of oxidation rates in the summer.

Another approach for modelling atmospheric chemistry of hydrogen uses Caltech/JPL 2D model [22]–[24]. This model solves the continuity equation for all important long-lived species and includes all the chemistry recommended by NASA for stratospheric modelling [25].

In order to highlight the potential impact of an increase of H_2 in the atmosphere, this model was used for two cases: (a) concentrations of H_2 and CH_4 are assumed to equal their approximate current global annual means at Earth's surface; and (b), the concentration of H_2 at Earth's surface is raised to 2.3 ppm.

Intermediate cases are discussed below. Fig. 2 presents simulated vertical profiles in concentrations of H_2 and CH_4 in the atmosphere for these two cases and a comparison of case (a) with recent measurements.

The model prediction for the vertical profile for case (b) is the dashed line in Fig. 1. Mixing ratios of CH_4 (solid line) and H_2 (long-dashed line) are simulated by the two-dimensional model for January at 60° to 70°N for case (a). The H_2 mixing ratio for case (b) is given by the short dashed line. The data (asterisks and crosses) are from the SOLVE balloon measurements [25]. The model uses a pressure coordinate, with altitude $z = H \ln(p0/p)$, where the scale height (H) = 6.95 km, p = pressure, and p_0=surface pressure; z is approximately equal to the geometric altitude.

The results show that the model correctly describes the relation between H_2 and CH_4 concentrations in the lower stratosphere, which reflects the balance of photo-oxidative reactions that are important for converting H_2 and CH_4 to H_2O.

The simulation model suggests that a fourfold rise in surface H_2 concentrations, such as might occur because of large rises in anthropogenic emissions, will lead to substantial moistening and cooling of the lower stratosphere and substantial decreases in stratospheric O_3.

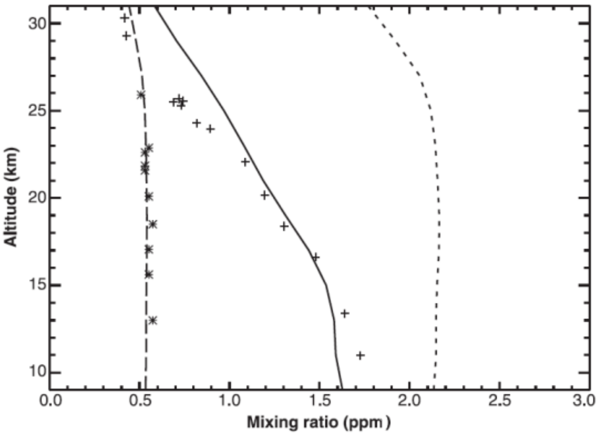

Fig. 2 Simulated concentrations of H_2 and CH_4

The direction and approximate magnitude of resulting changes in temperature and ozone concentration can be approximated as follows: An increase of 0.5 ppmv in stratospheric H_2O will cool the lower stratosphere by 0.5°C. Based on the climatology of the National Centers for Environmental Prediction Reanalysis data, this will increase the area of the northern polar vortex by 7% and that of the southern polar vortex by 4%. Finally, empirical data suggest that the polar vortices last 5 to 8 days longer when there is a 0.5°C temperature drop [25]. It is known that a colder vortex that lasts longer results in greater loss of ozone. Figure 3 depicts the percentage of ozone column density change. The O_3 depletion is about 5 to 8% in the boreal spring in the northern polar region, and about 3 to 7% in the austral spring in the southern polar region.

The reason for the larger change in the north versus the south is that the Antarctic ozone hole is already "saturated," whereas the Arctic ozone hole is not and has the potential to become more like the Antarctic. The model predictions outlined above suggest that anthropogenic emissions of H_2 could substantially delay the recovery of the ozone layer that is expected to result from the regulation of chlorofluorocarbons. However, we also note that the lower levels of chlorofluorocarbons expected several decades in the future should lead to less destruction of stratospheric ozone for a given amount of stratospheric moistening and cooling. Thus, the real consequences of a hydrogen economy will depend, in part, on whether it develops within about 20 years, when chlorofluorocarbon levels remain high; or more than 50 years in the future, when chlorofluorocarbon levels have substantially decreased.

Alternatively, we may devise a strategy that regulates the growth of the fuel cell industry, so that the impact on the ozone layer is minimized [25].

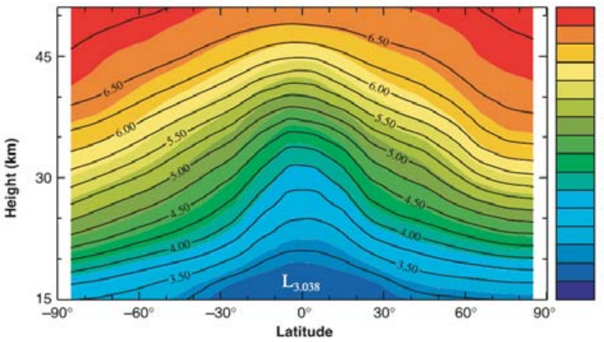

Fig. 3 The background H_2O mixing ratio and the increase of stratospheric H_2O in January due to the assumed fourfold increase of H_2, computed using the Caltech/JPL 2D model

III. GREENHOUSE EFFECT OF HYDROGEN

Scientists consider that any trace gas can be quantified as a greenhouse gas if, once released in the atmosphere, it interacts with the incoming solar radiation or with the outgoing terrestrial radiation [11].

Greenhouse gases exist in tiny fractions in the atmosphere—only parts per million and even per billion. A minor change in concentration could, trigger big, unanticipated, and possibly traumatic change in the atmosphere. "It is a highly leveraged situation," said John Firor, an atmospheric scientist at the National Center for Atmospheric Research in Boulder. Alan Lloyd, chairman of the California Air Resources Board and one of the 1990s' pivotal personages on the American hydrogen scene, appointed in early 1999: "Environmental pollution will likely represent the 'cold war' of the next century" [26].

The greenhouse effect of hydrogen was also simulated using STOCHEM model for global Lagrangian chemistry transport model [27]. The data used for this model were collected for 4 years and for three months, respectively. In the second case, the hydrogen emission source strength was increased so that a pulse containing an additional 40 Tg of hydrogen was emitted. The impact of the additional hydrogen on the composition of the model troposphere was followed by taking differences between the base and transient cases. These differences in composition between the two experiments were termed 'excess' concentrations. The effect of the additional emissions is the raise of the hydrogen burden, which decreases with an e-folding time of 2 years (close to the atmospheric lifetime of hydrogen).

The result of the increase in the atmospheric burden of hydrogen following the emission pulse was the variation of the concentrations for all the major troposphere free radical species and ultimately for troposphere ozone. Ozone production was stimulated in the transient case and that an 'excess' ozone burden quickly developed following the emission pulse. The 'excess' ozone burden decayed away with an e-folding time of about 2.5 years, close to the atmospheric lifetime of hydrogen.

In this model [27], the time-integrated radiative forcings were converted into Global Warming Potentials (GWPs) by comparison with the time-integrated radiative forcing of a reference gas (CO_2). So, the GWP of hydrogen was expressed as the ratio of the time-integrated radiative forcing resulting from the emission of 1 Tg of hydrogen compared with that from the emission of 1 Tg of CO_2 over a 100-year time horizon. The overall GWP for hydrogen was 5.8 over a 100-year time horizon [11].

A diagrammatic representation of the base and transient case experiments is given in Fig. 4 which follows the impact of an emission pulse of hydrogen on the composition of the model troposphere [17]. Fig. 4.a presents the globally-integrated hydrogen emissions over the four year's experiment, showing the emission pulse of hydrogen during January 1995. The effect of the additional hydrogen emissions is to raise the hydrogen burden in the transient experiment relative to the base case, generating an 'excess' hydrogen burden which is plotted out in Fig. 4.b. This 'excess' hydrogen decays away with an e-folding time of about two years which is close to the atmospheric lifetime of hydrogen.

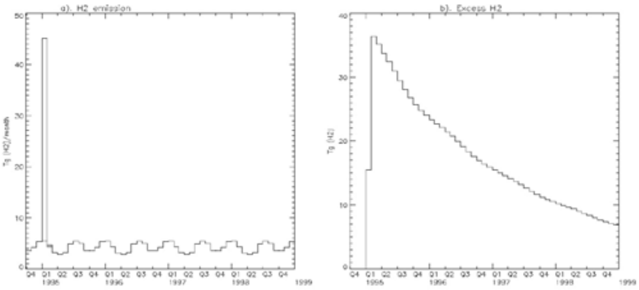

Fig.4 The time development in the composition of the global Lagrangian model troposphere following the emission of a 40 Tg pulse of hydrogen, showing in a) the global hydrogen emissions, b) 'excess' H2 burden

Because of the increased hydrogen burden in the transient experiment, a decrease is created in the OH burden which appears as a negative 'excess' in the OH burden, see Fig. 5.a, through the OH + H_2 reaction. Again, the "excess" OH burden decays away with the same e-folding time constant as the 'excess' hydrogen, close to two years. The reduced OH burden in the transient experiment, in turn, leads to a decrease in the OH + CH_4 reaction flux, see Fig. 5.b and the development of a small systematic difference in the globally-integrated methane loss rate from the base case [11].

The time development of the "excess" OH + CH_4 reaction flux follows that shown by the "excess" OH, decaying away with an e-folding time of just under two years. Since the OH + CH_4 reaction is the major loss process for methane, the hydrogen emission pulse leads to slightly different methane loss rates in the two model experiments and the methane burdens begin to diverge with time.

The time development of the 'excess' methane burden resulting from the emission pulse of hydrogen is shown in Fig. 6.a. The "excess" methane burden took about four years to reach its maximum before decaying away with the time constant associated with the methane adjustment time of about 12 years. As a result of the increase in the atmospheric burden of hydrogen following the emission pulse, adjustments followed on in the concentrations of all the major tropospheric free radical species and ultimately in tropospheric ozone. Fig. 6.b shows that ozone production was stimulated in the transient case and that an 'excess' ozone burden quickly developed following the emission pulse.

The "excess" ozone burden decayed away with an e-folding time of about 2.5 years, close to the atmospheric lifetime of hydrogen. Using the literature radiative forcing formulae, the time-integrated "excess" methane burdens in Fig. 6.a were converted into time-integrated radiative forcing, over a 100-year time horizon.

The 1 Tg hydrogen emission pulse produced a time-integrated methane radiative forcing of 0.35 mW m^{-2} year over a 100-year time horizon. The radiative forcing consequences of the tropospheric ozone burden changes were evaluated using an appropriate radiation code. The 1 Tg emission pulse produced a time-integrated ozone radiative forcing of 0.25 mW m_{-2} year over a 100-year time horizon [17]. These time-integrated radiative forcings were converted into Global Warming Potentials (GWPs) by comparison with the time-integrated radiative forcing of a reference gas, usually taken to be carbon dioxide, CO_2.

Here we define the GWP of hydrogen as the ratio of the time-integrated radiative forcing for a particular radiative forcing mechanism (whether through methane or ozone changes) resulting from the emission of 1 Tg of hydrogen compared with that from the emission of 1 Tg of CO_2 over a 100-year time horizon.

The fate of a 1 Tg emission pulse of CO_2 was described using the CO_2 response function of the Bern carbon cycle model [27]. On this basis, the GWP_{CH4} and GWP_{O3} for hydrogen were found to be 3.4 and 2.4, respectively, over a 100-year time horizon. The overall GWP for hydrogen is therefore 5.8 over a 100-year time horizon. As a consequence of the emission of hydrogen to the troposphere, changes occur in the global distributions of methane and ozone [27], the second and third most important greenhouse gases. Emissions of hydrogen lead to increased burdens of methane and ozone and hence to an increase in global radiative forcing. Hydrogen is accordingly an indirect radiatively active trace gas with a global warming potential of 5.8 over a 100-year time horizon.

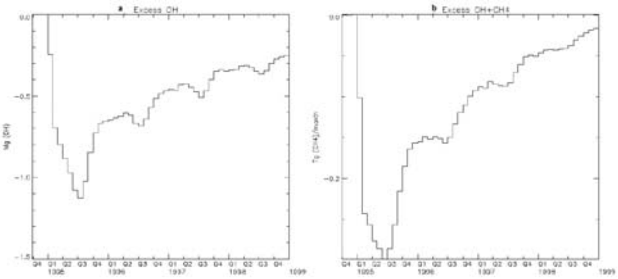

Fig. 5 The time development in the composition of the global Lagrangian model troposphere following the emission of a 40 Tg pulse of hydrogen, showing in a) "excess" OH burden, b) "excess" OH + CH_4

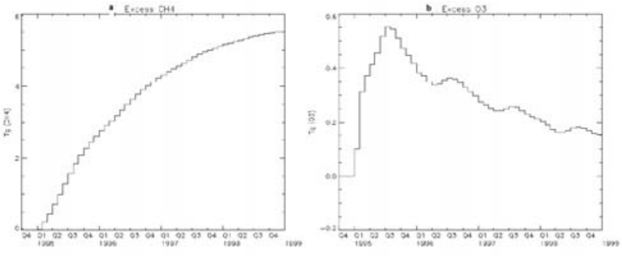

Fig. 6 The time development in the composition of the global Lagrangian model troposphere following the emission of a 40 Tg pulse of hydrogen, showing in a) “excess” CH_4 burden, and b) “excess” O_3 burden

The emission of hydrogen to the troposphere causes changes in the global distributions of methane and ozone the second and third most important greenhouse gases. Emissions of hydrogen lead to increased burdens of methane and ozone and increase the global radiative forcing. That is way we can say that hydrogen is an indirect radiatively active trace gas with a global warming potential [11].

These affirmations can lead to ask a simple question: a global hydrogen economy would have consequences for global warming and it would be better or worse than the fossil-fuel economy that it replaces?

As an answer, there are some estimations regarding the global hydrogen production capacity required to replace the entire current fossil-fuel based energy system (about 2500 Tg H_2 per year). The global hydrogen economy with a leakage rate of 1% can have a climate impact of 0.6% of the fossil fuel system it replaces. At a leakage rate of 10%, the climate impact would be 6% of that of the fossil fuel system.

IV. CONCLUSIONS

One can ask a simple question: if hydrogen’s benefits as a fuel are so great, why didn’t hydrogen make significant inroads into our energy systems years or even decades ago? The answer is not so simple. It involves a complex array of interlocking factors. First, there was no real need for hydrogen as long as there were ample supplies of oil and natural gas and as long as environmental worries were not a concern. Fossil fuels were cheap, and hydrogen was as much as several times more expensive. Liquid hydrogen, the coldly exotic stuff that powers the Space Shuttle and experimental BMW sedans today, was a laboratory curiosity four or five decades ago [26].

Used as a fuel, it would reduce and eventually eliminate at least the man-made share of CO_2 deposited in the atmosphere. Switching to hydrogen energy—even perhaps to hydrogen from fossil fuels as a stopgap measure—may help save our children’s health and perhaps their lives.

The potential environmental impact of hydrogen can be highlighted in few lines:

- increased hydrogen concentration can lower the natural oxidizing capacity of the atmosphere, increasing in this way the lifetime of air pollutants and greenhouse gases;
- it can increase water vapour concentration in the atmosphere, having consequences in cloud formation, stratospheric temperatures and ozone loss;
- it could exceed the uptake capacity of hydrogen by micro-organisms in the soil, currently the main way in which hydrogen is removed from the atmosphere;
- if hydrogen is generated using electricity derived from burning coal, nitrogen oxides emissions could increase significantly;
- generating hydrogen from fossil fuels could lead to increased emissions of carbon dioxide, which would accelerate global warming, unless the CO_2 is captured and stored;
- generating hydrogen from sustainable sources would reduce emissions of carbon monoxide and NO_x, with a consequent fall in tropospheric ozone levels. This would improve air quality in many regions of the world. Furthermore, CO_2 emissions would be reduced, thereby slowing the global warming trend.

We can say that there is a confluence of drivers that point in the same direction – towards hydrogen. These drivers include the requirement for a reduction in CO_2 emissions, appalling urban air quality, legislation dictating zero-emission vehicles, progress in fuel cell technology, a move toward the use of local resources for energy production, the need to store intermittent renewable energy concerns about fossil-fuel resources, as well as the security of energy supplies.

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