

The Hydrogen Economy in the 21st Century: A Sustainable Development Scenario

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Excerpt of a Paper submitted to the International Journal of Hydrogen Energy. March, 2002.

As part of a collaborative study with Tokyo Electric Power Company (TEPCO) on examining future perspectives for fuel cells, a long-term hydrogen-based scenario of the global energy system has been developed. The scenario illustrates the key role of hydrogen in a long-term transition towards a clean and sustainable energy future. In an affluent, low-population-growth, equity and sustainability-oriented B1-H₂ world, hydrogen technologies experience substantial but plausible performance and costs improvements and are able to diffuse extensively. Corresponding production and distribution infrastructures emerge. The global hydrogen production system, initially fossil-based, progressively shifts towards renewable sources. Fuel cells and other hydrogen-using technologies play a major role in a substantial transformation towards a more flexible, less vulnerable, distributed energy system which meets energy needs in a cleaner, more efficient and cost-effective way. This profound structural transformation of the global energy system brings substantial improvements in energy intensity and an accelerated decarbonization of the energy mix, resulting in relatively low climate impacts.

The B1-H₂ scenario is based upon the IIASA-B1 scenario developed for the IPCC Special Report on Emission Scenarios (SRES, 2000), with updated information on technology characteristics for hydrogen technologies gathered from a technology assessment. The B1 world has been chosen because it provides a good context to outline the role that hydrogen could play in the global energy system if ideal conditions for its penetration were in place.

The B1-H₂ scenario illustrates a relatively smooth transition towards a post-fossil global energy system. Fossil fuels still dominate the primary energy supply until 2050, but during this period, the system shifts away from coal and oil, which reduce their shares substantially, towards natural gas. In turn, natural gas operates as the main transitional fuel to the post-fossil era, which unfolds in the second half of the 21st century. During this period, remarkable structural changes become evident. Renewable energy sources, in particular biomass, increase their shares substantially. A transition to a decentralized energy system takes place.

Likewise, the amount of final energy per unit of GDP decreases at an accelerated rate, as the economy shifts towards less energy, and material-intensive activities, and more efficient end-use technologies improve and diffuse. At the global level, final-energy

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intensity declines at an average rate of 2 percent per year between 1990 and 2100. Although different world regions follow different paths, fast improvements are evident in all of them, particularly in the developing regions where economic growth and capital turnover are faster.

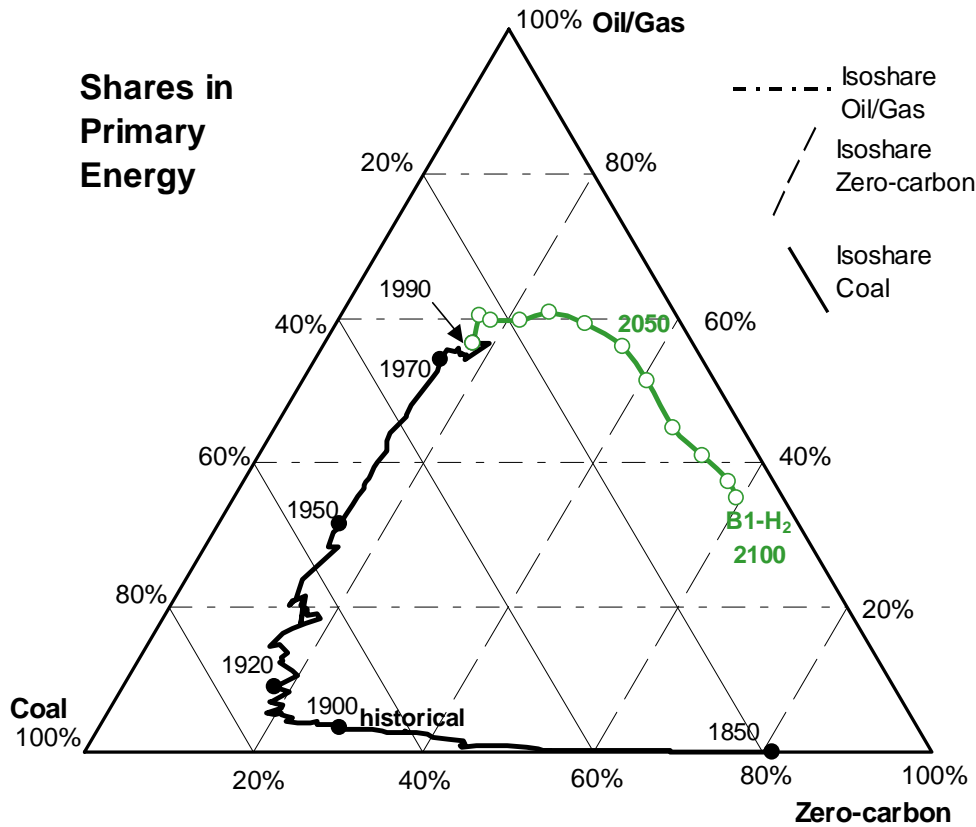


Fig 1. Global shares in primary energy use, coal, oil/gas, and non-fossil energy, illustrated with an “energy triangle” (in percent). Constant market shares of coal, oil/gas, and non-fossil (0-carbon) energies are denoted by their respective isoshare lines. Historical data from 1850 to 1990 (black) are based on on Nakićenović *et al.*, 1998. The development in the B1-H₂ scenario is shown for the years 1990 to 2100 (ten year time steps).

Globally, hydrogen is produced with a diversified mix of technologies (see Fig. 2). Steam reforming of natural gas and gasification of biomass play the leading roles. Along the most part of the time horizon, steam reforming holds the largest share of supply. In the last decades of the 21st century, however, the rapidly increasing production from biomass becomes the most important supply source at the global scale. Significant contributions are also made by the solar thermal technology and, to a lower extent, by coal gasification. In the regions where coal gasification is introduced, it operates as a transition technology towards a renewable-based hydrogen supply structure. Nuclear high-temperature reactors and electrolysis play marginal roles. Still, they constitute valuable complementary options in particular niche markets. Following considerable economic and technological structural changes and substantial energy efficient improvements that reduce the demand for final energy carriers in the long-term, global hydrogen production peaks at 330 EJ/year around the year 2080 and declines afterwards.

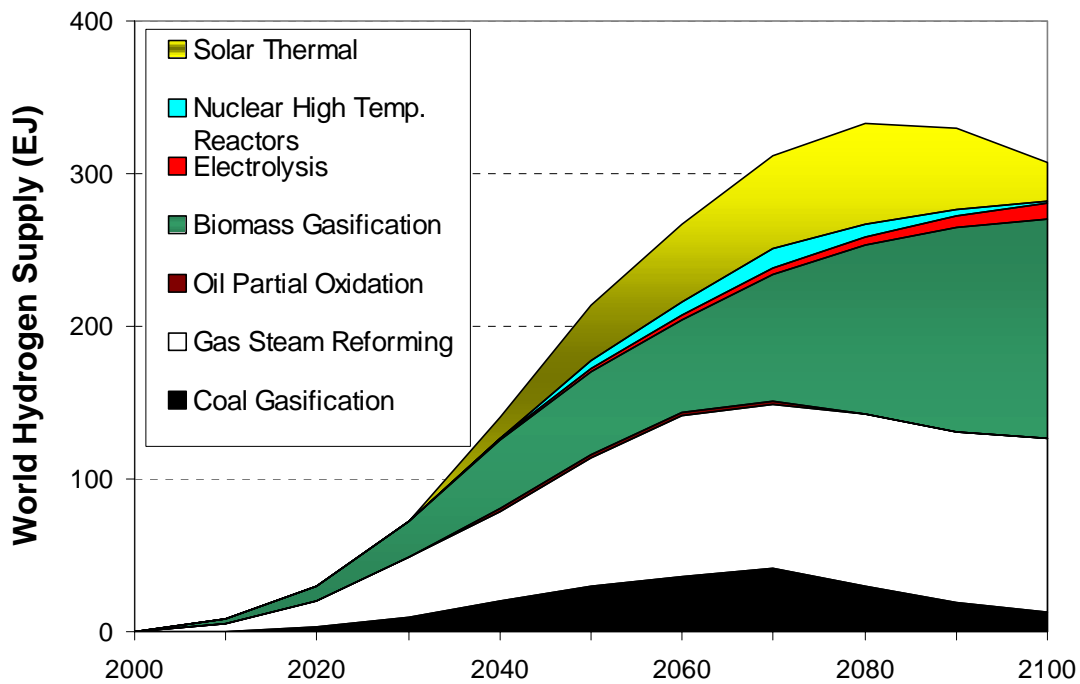


Fig. 2. Global hydrogen supply mix in the B1-H₂ scenario. Steam reforming of natural gas and gasification of biomass are the dominant technologies.

In the B1-H₂ scenario, electricity production strongly shifts away from traditional centralized fossil-based technologies towards post-fossil and zero-carbon generation systems. Such transition contributes substantially to achieve sustainable-development goals in the electricity system. By the end of the 21st century, hydrogen-based fuel cells, renewables and nuclear power plants become the leading suppliers, while coal and oil power plants are completely phased out. The only fossil fuel that remains is natural gas and its share is small compared to other options. However, natural gas power plants, more specifically the gas-fired combined cycle, play an important role “bridging” the long-term transition to advanced post-fossil systems. Fig. 3 presents the market shares of generation technologies in the global electricity mix for the years 2020, 2050 and 2100.

The transformation of the global electricity sector is substantial, not only regarding primary fuels, but also regarding its very nature. Large-scale centralized power plants give way to small-scale distributed generation systems that operate nearer the point of use. A substantial amount of highly efficient, cost-effective and less vulnerable micropower systems penetrates the global electricity markets at a quick pace, driven by technological breakthroughs and accompanied by a favorable institutional and regulatory revolution (Dunn, 2000).

By the end of the 21st century, decentralized systems, mainly hydrogen-based fuel cells and on-site solar photovoltaics installations, hold almost a 50 percent share of the global electricity market. Fuel cells, in particular, experience a dramatic growth. Electricity co-generation in industrial and residential stationary fuel-cell applications

and generation from mobile hydrogen-based fuel cells in the transportation sector (e.g. fuel cell-powered cars generating electricity while parked) become major contributors to the generation mix, accounting for approximately 38 percent of the global generation market in 2100.

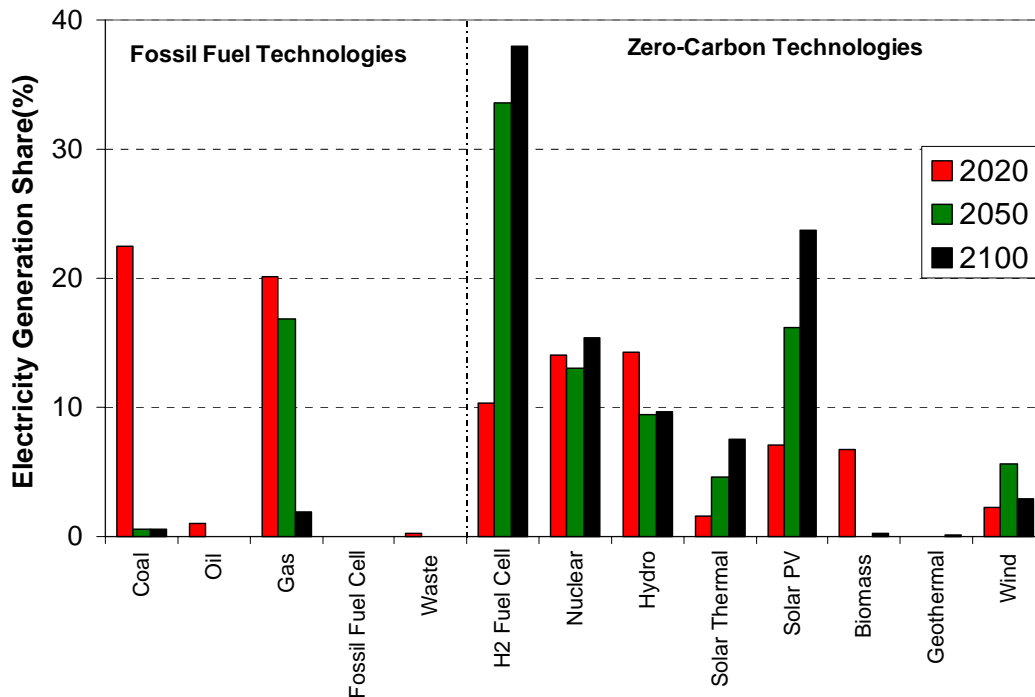


Fig. 3. World market shares for aggregate electricity generation technologies in the years 2020, 2050 and 2100 in the B1-H₂ scenario. It must be noticed that, although hydrogen fuel cells (H₂FC) are shown here within the group of zero-carbon technologies, they only become a true zero-carbon option when the hydrogen production system becomes non-fossil based.

During the course of the 21st century, the final energy mix of the B1-H₂ scenario changes considerably, as the trend towards cleaner, more flexible and convenient energy carriers continues (see Fig. 4). Solid fuels, such as coal and biomass, are gradually phased out of the final energy market. Oil products, today's prevailing fuels, reduce their share drastically. Grid-delivered energy carriers as electricity and hydrogen increasingly dominate the final-energy mix. Hydrogen, in particular, driven by the penetration of efficient end-use technologies, increases its share dramatically, accounting for approximately 49 percent of the global final consumption by the end of the 21st century, and becomes the main final energy carrier.

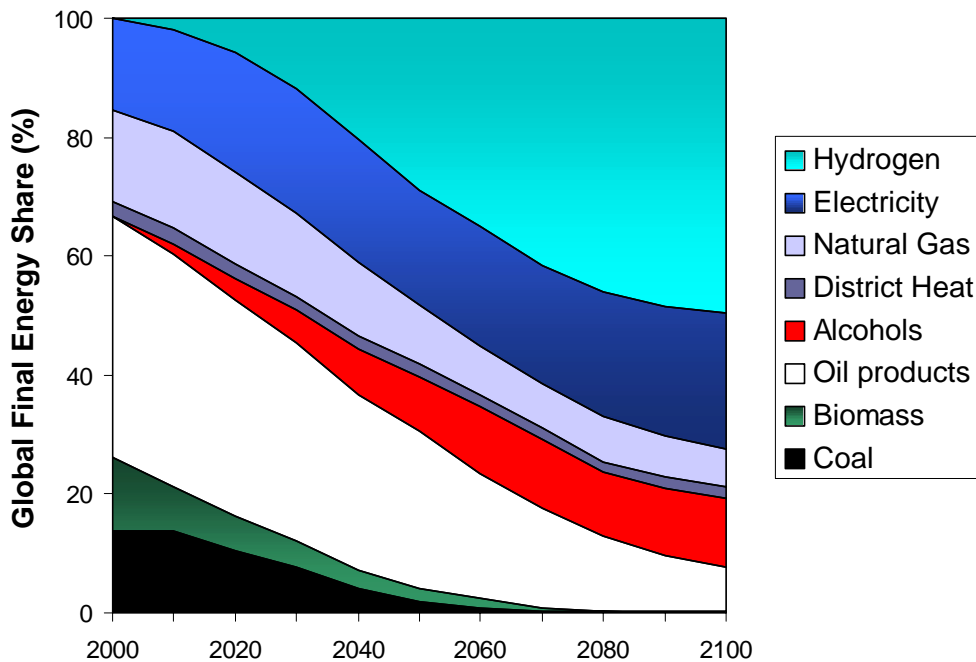


Fig. 4. Evolution of global market shares of different final-energy carriers for the period 1990-2100 in the B1-H₂ scenario. The alcohols category includes methanol and ethanol.

Fuel cells and related technologies drive forward this transformation. They play a key role in the transportation sector, residential/commercial stationary applications and in key industrial niches. In the transportation markets, for instance, fuel cells penetrate extensively, displacing currently prevailing technologies such as the internal combustion engine. Fig. 5 presents the evolution of the market share of fuel cells versus the aggregate of other technologies in the global transportation sector during the 21st century in our scenario. The aggregate share of fuel cells is already 51 percent in the year 2050 and rises to 71 percent in 2100. The main role is played by hydrogen-based fuel cells, but alcohol-based fuel cells operate as important complementary options.

From today's perspective, if penetration of hydrogen and fuel cells is to be successful, opportunities in different sectors must be tapped. Transportation constitutes indeed a primary target market for both fuel cells and hydrogen. Market potential is huge and benefits can be very significant. However, barriers for the penetration, ranging from supply infrastructures to onboard storage problems and perceived safety risks, appear to be high. Other market segments, where barriers are less severe, may offer attractive opportunities to stimulate early introduction. Potential synergies between, for instance, the buildings and vehicles markets could be used to make hydrogen a more attractive alternative and help to overcome the initial infrastructure barrier (Lovins and Williams, 1999).

This calls for a coordinated strategy for the deployment of hydrogen technologies in different market segments, in order to profit from potential synergies and benefit from the costs reductions as the volume of manufacturing and sales builds up. R&D,

demonstration and commercialization strategies must be targeted at overcoming the barriers specific to each market segment while exploiting the advantages of hydrogen (NHA, 2000).

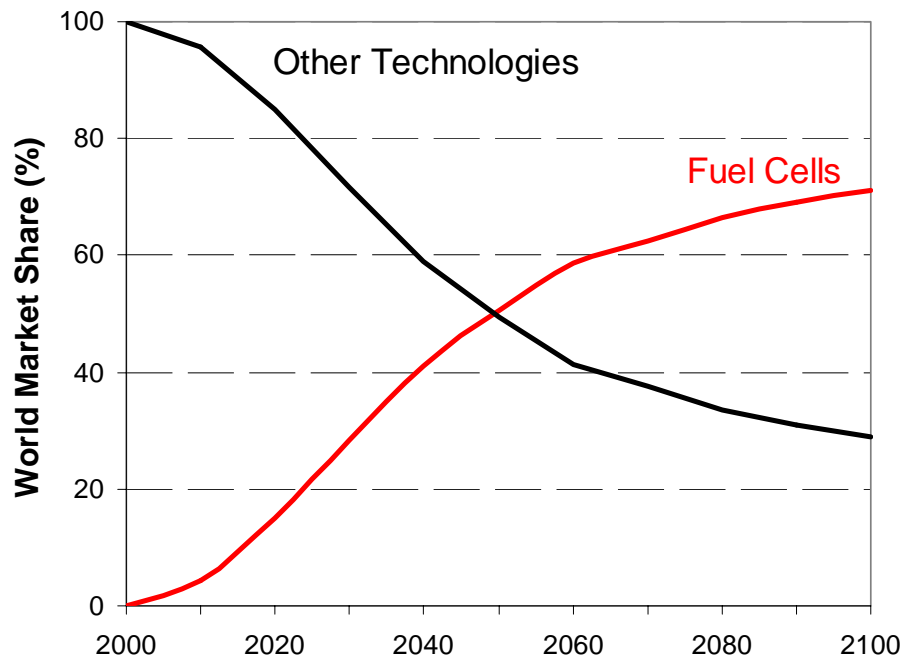


Fig. 5. Evolution of the market share of fuel cells Vs the aggregate of other technologies in the global transportation sector in the B1-H₂ scenario.

The CO₂ emissions resulting in the B1-H₂ scenario are presented in Fig. 6. In order to provide an adequate perspective of the effects of this hydrogen-based energy path we compare this emissions path to a “dynamics-as-usual case”. Generally, “dynamics-as-usual” scenarios assume that rates of change for the main scenario drivers, such as technological enhancement, demographic changes, and economic development follow historical experience. Hence, they tend to result in relatively high levels of GHG emissions and climate impacts. As the dynamics-as-usual scenario, we selected the IIASA B2 scenario developed for the IPCC Special Report on Emission Scenarios (SRES, 2000, Riahi and Roehrl, 2000). In B2, global carbon emissions from energy use and industrial sources rise from 6.2 GtC in 1990 to 14.2 GtC in 2100. In contrast, CO₂ emissions in B1-H₂ peak at about 10.5 gigatons of carbon (GtC) in 2040 and reach 5.7 GtC in 2100, a lower value than in 1990.

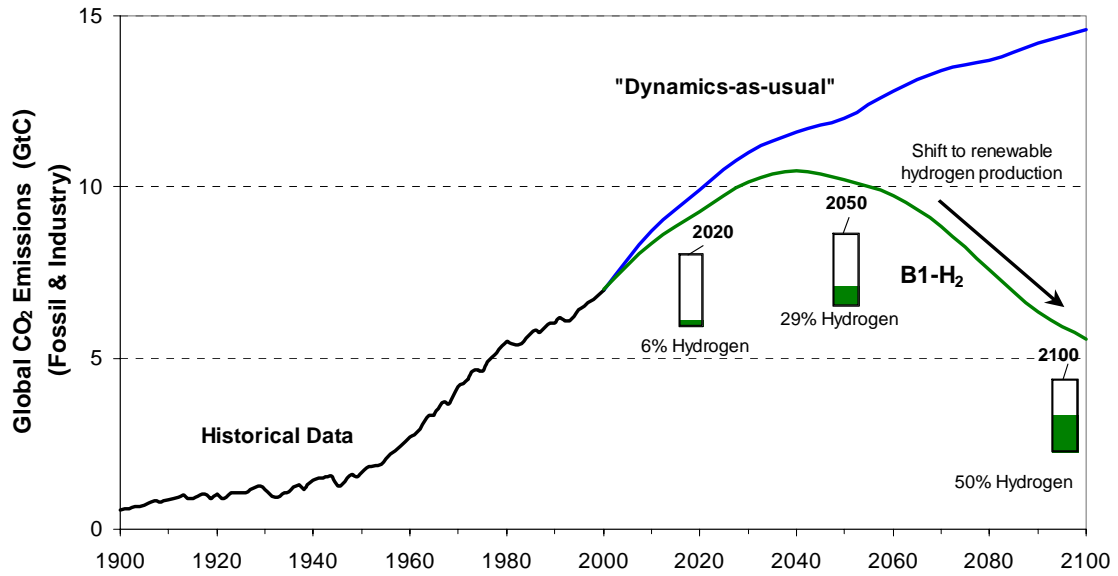


Fig. 6. Carbon emissions in the B1-H₂ scenario (green) compared to the emissions for a dynamics-as-usual development (blue), and actual development from 1900 to 2000.

An intensive decarbonization of the energy supply accompanies the structural transformation in the B1-H₂ scenario. Fig. 7 presents the evolution of the carbon intensity of the global primary energy supply for the 20th century and the trend in the B1-H₂ scenario for the 21st century. The historical development from 1900 to 1990 shows a persistent but slow decarbonization trend of the world's energy system at approximately 0.3 percent per year. In B1-H₂ the decarbonization trend is substantially accelerated. Between the years 1990 and 2100, the carbon intensity of global primary energy is reduced at an annual average rate of 0.8 percent per year, as the energy system becomes increasingly non-fossil based.

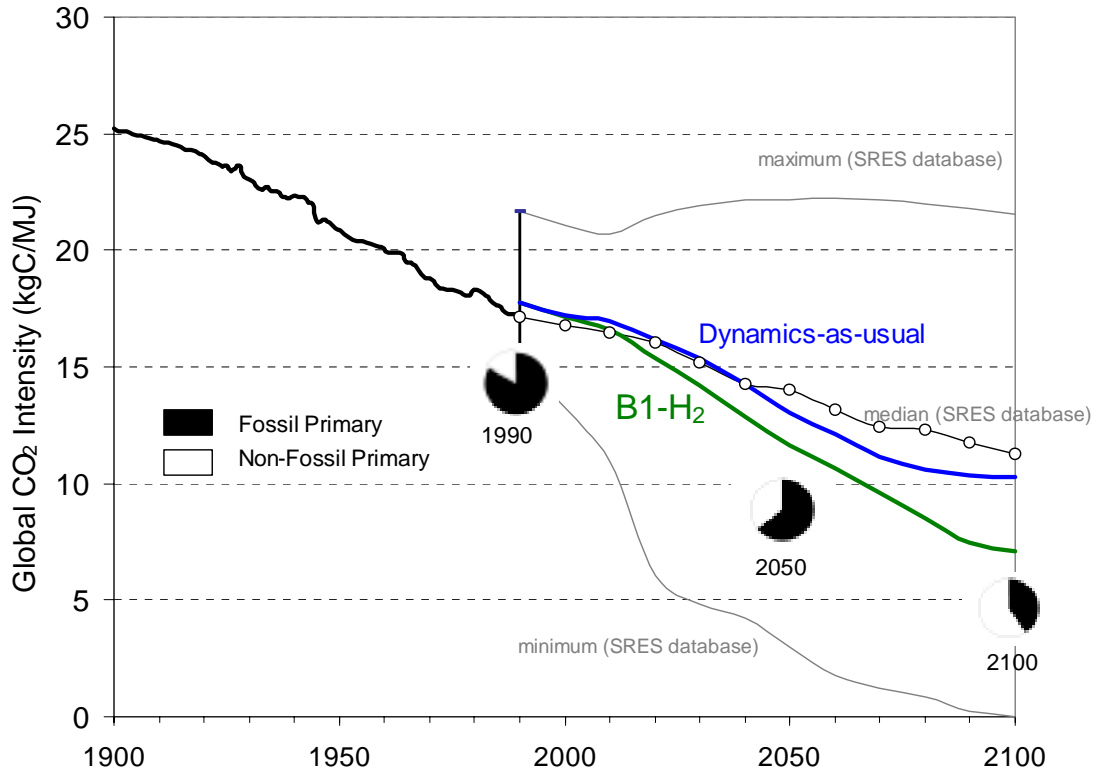


Fig. 7. Decarbonization trend (carbon intensity reduction) of global primary energy supply. Actual development from 1900 to 1990 and in the B1-H₂ and dynamics as-usual scenarios from 1990 to 2100. For comparison, the maximum, median and minimum carbon intensity trajectories from the database of the IPCC Special Report on Emission Scenarios (SRES) are also displayed (Morita and Lee, 1998, SRES, 2000).

The resulting atmospheric carbon concentrations of the scenarios are illustrated in Fig 8. The carbon concentrations climb steadily under dynamics-as-usual assumptions and reach 600 parts per million by volume (ppmv) in 2100. In contrast, B1-H₂ depicts a route to stabilizing the concentrations at about 500 ppmv. As illustrated by Fig 8, even the upper bound of the uncertainty range for the B1-H₂ scenario stabilizes at 540 ppmv, which is considerably below the best-guess estimate of the dynamics-as-usual scenario. This highlights the key role that hydrogen could play to “hedge” against the risks of climate change. Pursuing the penetration of hydrogen within the current hydrocarbon-based energy system, while being compatible with the dominant technological regime, could pave the way for the long-term transition to an energy system with low release of carbon to the atmosphere.

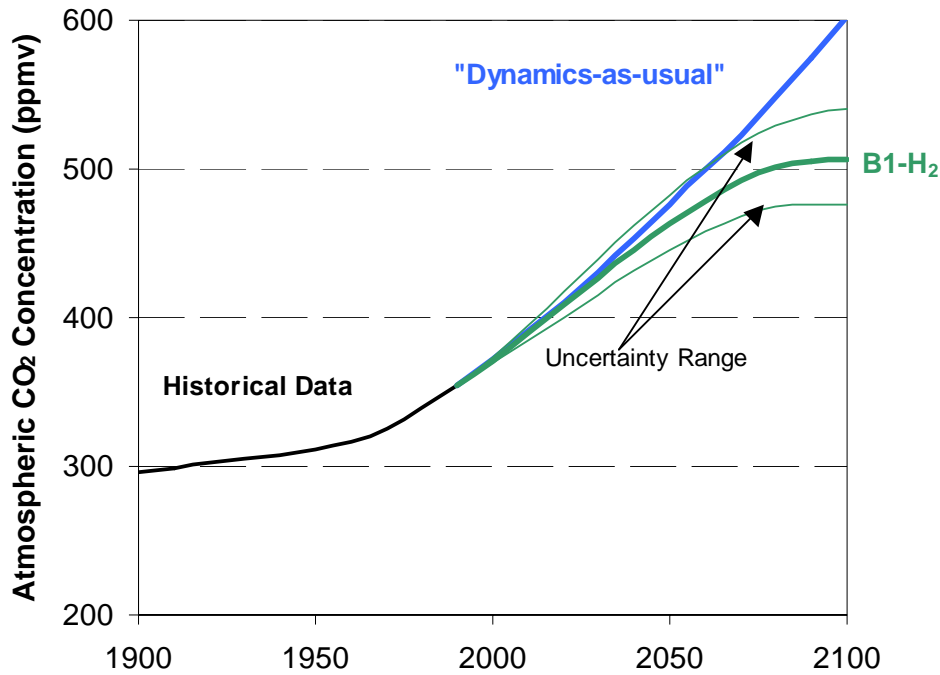


Fig 8: Atmospheric CO₂ concentrations. Historical development from 1900 to 1990 and future trajectories for the B1-H₂ (green) and the “dynamics-as-usual” scenario (blue). The thin lines depict the uncertainty range for B1-H₂ given by the variation of the assumed CO₂ fertilization effect.

The unfolding of a sustainable hydrogen-based energy system such as the one portrayed here could bring profound changes to the current energy markets and standard business practices. In particular, the emergence of fuel cells and other distributed electricity generation alternatives could alter fundamentally the structure of the power generation and transportation business, driving to the creation of new products and values, service standards, innovative business partnerships etc. Fuel cells have significant potential to become an important element of the portfolio of options to meet ever-increasing demands for energy services while responding to more stringent reliability and power quality standards, mounting environmental constraints, cost-effectiveness pressures and other challenges that energy systems will face in the future. Achieving the large-scale transformations of the global energy system that result in a clean and sustainable hydrogen future requires substantial efforts in a number of fields and the involvement of many different social actors. In particular, the combination of government measures and business actions is necessary to stimulate the growth of a sustainable hydrogen energy industry.

Acknowledgements

This collaborative study has been sponsored by the Tokyo Electric Power Company (TEPCO). We would like to thank Leo Schrattenholzer, Project Leader of the Environmentally Compatible Energy Strategies Project at IIASA, Takashi Okano, Research Group Leader of the Corporate Planning Department at TEPCO, and Akifusa Hagiwara, Material Science Group Leader of the Energy and Environmental R&D Center at TEPCO for their continued support and their very useful comments on the draft versions. We would also like to extend our appreciation to Pat Wagner from IIASA for her editorial assistance.

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