Global Possibilities of Future Methane and Hydrogen Economies

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Jules Verne, the father of science fiction, wrote several books using ideas that eventually became reality. Some examples include: *From the Earth to the Moon* in 1866, *Twenty Thousand Leagues Under the Sea* in 1870 where he envisions submarines, *Robur the Conqueror* in 1886 where he describes the precursor of helicopters, and *The Mysterious Island* in 1875 where he wrote:

> *Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable.*

Vaitheeswaran (2003) asks, "Could the man who forecast the development of such technological marvels as submarines, helicopters, and space travel have gotten energy right, too?" We believe that the answer is most likely positive.

Hydrogen accounts for approximately 75% of the universe's mass and is the most abundant of all elements. Stars are made mainly of hydrogen. However, hydrogen does not generally exist in a free state in Earth. Consequently, it has to be extracted from different materials including, for example, biomass, fossil fuels, and water. This means that it takes energy to free hydrogen for use, no matter how it is produced. As a result, hydrogen is not strictly an energy source but an energy carrier much in the same way as electricity.

At present, while society is deeply concerned about the environment, hydrogen might emerge as a white knight. There is evidence that, since 1850, the relative hydrogen consumption has been increasing steadily **(Fig. 1).** Research shows continuous decarbonization from 1850 to 1970. At this point, the hydrogen/carbon (H/C) ratio becomes approximately constant (in the order of 1.8). Hefner (2002) describes this history for the US as follows: "For more than 100 years, free markets and the ingenuity of humankind worked efficiently to decarbonize our energy systems… . It was only starting in the 1950s, when governments began to tinker with price controls and later, reacting to the 'sky is falling' cries of shortages by the energy industry, allocated fuels among sectors of consumers, that we once again began to recarbonize the energy system." The recarbonization period described by Hefner occurs between approximately 1970 and 2006. However, the Global Energy Market (GEM) model tends to show a slight improvement in the H/C ratio as we advance toward the year 2030. This suggests an increase in production of natural gas which, we anticipate, will pave the way to an "energy revolution that will transform an industry, change our lives, and maybe even save the planet" (Vaitheeswaran, 2003).

Pessimists vs. Optimists

Notwithstanding the strong possibilities of natural gas and perhaps hydrogen economies, there is concern within some factions of the energy industry about a potential energy crisis this century. Those who are concerned about depletion and subsequent harm to society are usually referred to as the pes-

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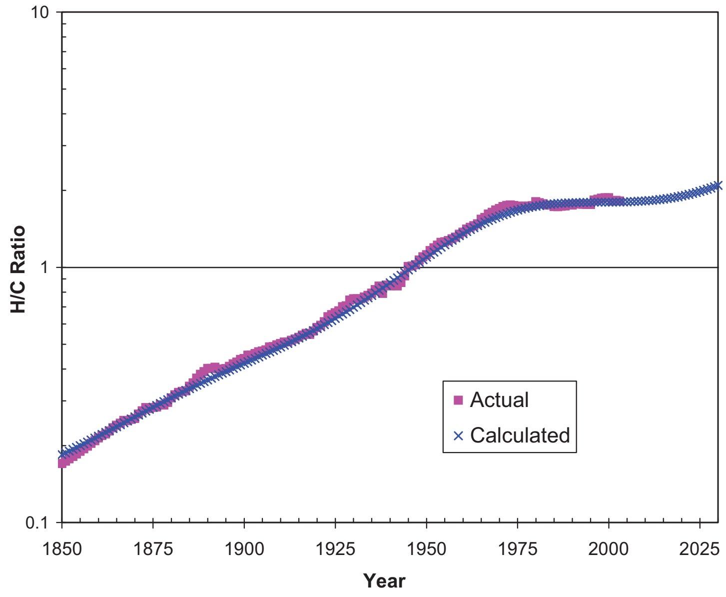

Fig. 1—World H/C ratio, a good proxy for environmental quality.

simists, e.g., Banks (2005), Campbell and Laherrere (1998), Deffeyes (2001), Goodstein (2004), Simmons (2005), and Tertzakian (2006). Those who believe society will not be undermined, since there are abundant hydrocarbons and fungible resources, are the optimists, e.g., Adelman (1993), Economides and Oligney (2000), Hefner (2002), Radetzki (2002), and Tilton (2002).

The pessimists point out that petroleum resources are fixed physical stocks that will eventually be depleted. The optimists view petroleum as a working inventory that is constantly being renewed as required when it is extracted, by movement from the petroleum resource base to the reserve domain.

In the case of oil and natural gas, eventually there will be a maximum peak in production. The question is if it will occur sooner or later, and if it will happen because of depletion or because of substitution to other energy sources, perhaps unconventional or non-fossil.

Recent work (Aguilera, 2006; Aguilera and Aguilera 2008; Aguilera et al. 2009) suggests that there are enough hydrocarbons, available at production costs far below current prices, for society to substitute alternative sources before depletion becomes a problem. For example, the global endowment of conventional natural gas from 937 petroleum provinces around the world is in the order of 15,100 Tcf. The endowment of tight gas sands, which we are equating to technically recoverable reserves, is estimated at approximately the same volume (Aguilera et al. 2008).

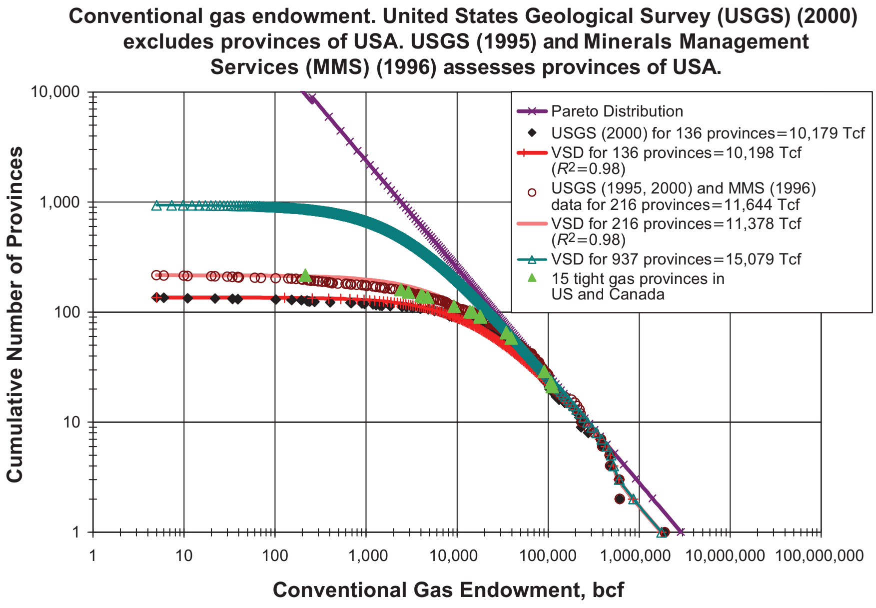

Fig. 2—World conventional natural gas endowment calculated with variable shape distribution (VSD) model.

However, the successful transition after peak oil or peak natural gas production depends on whether adequate investment in alternative sources takes place on a timely basis. The ability of technological advancement to offset the cost-increasing effects of depletion will be fundamental.

Temporary shortages might still occur due to problems that include lack of spare capacity, cartels, political instability, hurricanes and other natural disasters, strikes, shortage of qualified workers, shortage of refining capacity, commodity manipulation by speculators, and more recently, the power of national oil companies.

Global Energy Market

A GEM model leads to what we have called the "2030 1/3 forecast." It indicates that global energy needs will be met by approximately 1/3 of liquids, 1/3 of solids, and 1/3 of gases by 2030.

A pentagon with the following 5 corners and the global population represented in the center describes the philosophy of the GEM model.

Corner 1—Historical and forecasted future energy consumption

Corner 2—Historical and forecasted future fraction contributed by each primary energy source

Corner 3—Actual and forecasted consumption rate of each source

Corner 4—Estimated energy source availability

Corner 5—Cumulative long-run supply curve that estimates the production costs of the world's recoverable hydrocarbon volumes

Corner 4 answers the question whether there are enough volumes of gas and other resources, perhaps nonconventional or nonfossil, to supply the rates forecasted in corner 3, by plotting recoverable hydrocarbon volumes vs. the number of recognized petroleum provinces around the world.

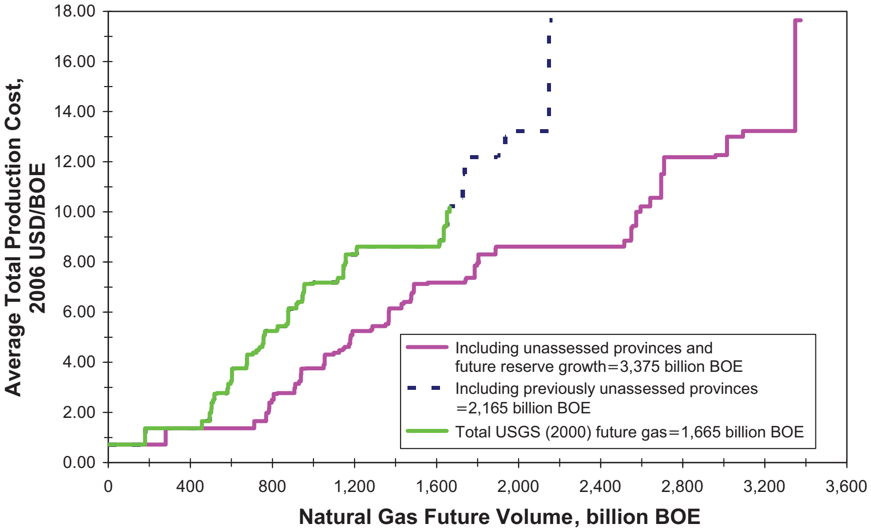

Fig. 3—Cumulative long-run supply curve for conventional gas.

For conventional natural gas this is shown in **Fig. 2.** The data come from the USGS *World Petroleum Assessment 2000*. The theoretical values were calculated with a variable shape distribution (VSD) model (Aguilera, 2006). For hydrogen, an energy carrier, the availability would be essentially unlimited.

The actual gas endowment for the lower curve in Fig. 2 corresponds to 136 petroleum provinces, excluding the United State (USGS, 2000). The gas endowment estimated by the USGS (10,200 Tcf) compares well with 10,200 Tcf calculated by the VSD model with a coefficient of determination (R^2) of 0.98. The middle curve corresponds to 216 petroleum provinces, including the United States. The USGS (2000) gas endowment in this case is 11,600 Tcf. This compares well with the 11,400 Tcf calculated by the VSD model. Note that these volumes do not include reserve growth, unconventional gas (tight gas, shale gas, coalbed methane, and natural gas hydrates), offshore gas provinces with water depths greater than 2000 m in some petroleum provinces and 4000 m in others. Similar fits and R^2 values were obtained for the cases of oil and natural gas liquids thus further validating the VSD model (Aguilera, 2006).

Once the model was validated, it was used to estimate the recoverable conventional gas volumes of the recognized 937 petroleum provinces of the world, out of which 528 had not been evaluated previously. The balance of 409 petroleum provinces had been evaluated by the USGS but only 216 of those presented gas endowment volumes that were useful mathematically. The other 193 petroleum provinces showed either zero, nonavailable or <100 Bcf of gas. The top curve of Fig. 2, generated by the VSD model, corresponds to 937 provinces and gives a conventional endowment of 15,100 Tcf of gas for the world. In addition, recent work (Aguilera et al. 2008) suggests that there are other 15,100 Tcf in tight gas formations worldwide.

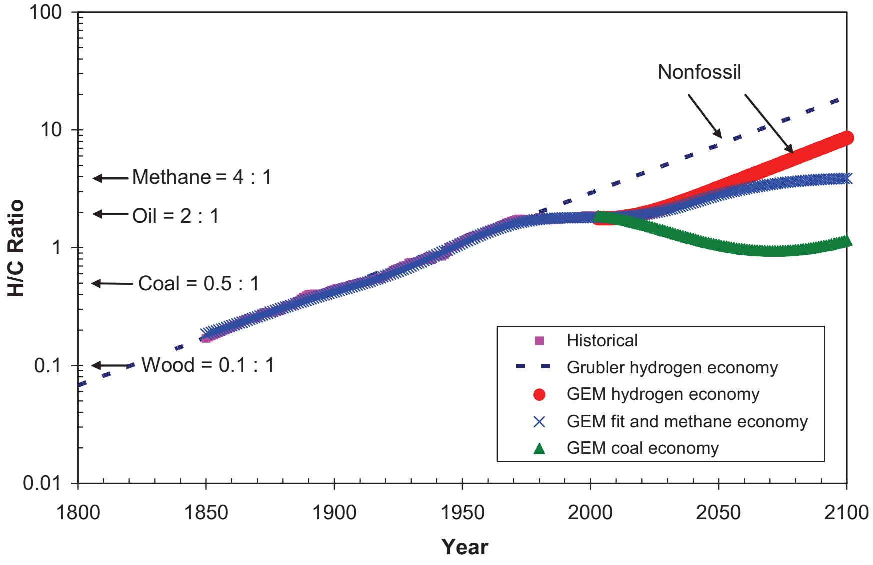

Fig. 4—H/C ratio; historical, hydrogen, methane, and coal economies.

These results indicate that there are enough recoverable hydrocarbons to satisfy energy requirements for the next several decades. In our opinion, this will provide sufficient time for society to substitute to other energy sources, perhaps unconventional or nonfossil.

Possibilities of a Future Methane Economy

The terminology used in this article is taken from the USGS *World Petroleum Assessment 2000,* and includes:

Cumulative Production: The reported cumulative volume that has been produced.

Endowment Volume: The sum of the known volume (cumulative production plus remaining reserves) and undiscovered volume.

Future Volume: The sum of the remaining reserves and undiscovered volume. Cumulative production does not contribute to the future volume, neither does reserve growth.

Known Volume: The sum of cumulative production and remaining reserves.

Petroleum Province: A USGS-defined area having characteristic dimensions of perhaps hundreds to thousands of kilometers encompassing a natural geologic entity (for example, sedimentary basin, thrust belt, delta) or some combination of contiguous geologic entities.

Remaining Reserves: The volume in discovered fields that has not yet been produced. Remaining reserves are equal to known volumes minus cumulative production.

Reserve Growth: The increases in "known" volumes that commonly occur as fields are developed and produced. It is synonymous with field growth and appreciation.

Undiscovered Volume: The volumes postulated by the USGS, from geologic information and theory, to exist outside of known volumes.

The question about the possibilities of a future methane economy is answered by the cumulative long-run supply curve presented in **Fig. 3.** The upper continuous solid curve shows USGS (2000) assessed future gas vs. average gas production costs for 409 provinces. The upper dotted curve represents all 937 provinces of the world. The lower solid curve includes provinces that had been previously assessed and unassessed, as well as reserve growth (Aguilera, 2006).

The conclusion is reached that there are significant volumes of conventional natural gas that are available at production costs far below current prices for society to substitute alternative sources before depletion becomes a problem.

In addition, a new study (Aguilera et al. 2008) shows that there are potentially other 15,100 Tcf of technically recoverable reserves in tight gas sands. We have not evaluated the endowment of coalbed methane and shale gas. However, there are estimates of resources in coalbed methane (3,510 to 9,180 Tcf) and shale gas (1,483 to 1,589 Tcf) (French Petroleum Institute [IFP], 2006), which when put together with the natural gas endowments presented in this article, suggest that there is a brilliant future for a global methane economy. The vision of some natural gas mavericks (Durbin, in Sturken, 1991; Hefner, 1999; Economides and Oligney, 2000) can certainly be realized.

Possibilities of a Future Hydrogen Economy

The GEM model supports the work of experts visualizing a bright future for a hydrogen economy. There are clearly problems related to safety, storage, and supply of hydrogen. However, we consider the line of thinking of the skeptics along the same lines of the pessimists mentioned in the introduction of this article; the common threat among the skeptics and pessimists is ignoring the creative power of the "ultimate resource" (Simon, 1981).

The combustion of hydrogen produces water and oxygen. This makes it ideal as an energy carrier that can help reduce environmental harm including our contribution to global warming (e.g., emissions of carbon dioxide and other greenhouse gases).

Presently, most of the hydrogen production in the world is obtained from natural gas by a process called "steam reforming" (Crabtree et al. 2004). Using gas, the cleanest burning fuel, helps the environment but does not eliminate the problem of CO_2 production. To make the use of hydrogen sustainable in the long run, society must find a means of economically producing hydrogen from nonfossil fuels. This will require continuous R&D.

Crabtree et al. (2004) have described a hydrogen economy as a "network composed of three functional steps: production, storage, and use." The problem at present is competing with the cost, efficiency, and reliability of fossil fuels in each one of the three steps. For example, in the production phase from natural gas, hydrogen is about four times the cost of gasoline for an equivalent amount of energy. Other production methods are even more expensive. Some of the sources for producing hydrogen include water, solar, wind, biomass, and nuclear.

Crabtree et al. explain the storage problems and associated costs as follows: "Hydrogen can be stored in pressurized gas containers or as a liquid in cryogenic containers, but not in densities that would allow for practical applications… hydrogen can be converted to electricity in fuel cells, but the production cost of prototype remains high: USD 3,000 per kilowatt of power produced for prototype fuel cells (mass production could reduce this cost by a factor of 10 or more), compared with USD 30 per kilowatt for gasoline engines." Based on past experience, reductions in costs will be achieved through fundamental research. Once this is achieved, development will lead to several uses by society.

Fig. 4 shows a plot of the H/C ratio vs. time starting in 1850 and going to the year 2100. This type of plot is based on original work by Marchetti (1985). The historical trend and the dashed line, representing a hydrogen economy, are based primarily on work by Grubler (2004). The blue 'x' line is a best match of the historical data between 1850 and 2005 developed with the GEM model (Aguilera and Aguilera, 2008). The comparison is good, with an R^2 of 0.99. The same symbol is used to show a forecast to the year 2100. This curve is calculated based on the average H/C ratios shown on the graph for methane, oil, coal, and wood. As a result, the curve can never go above an H/C ratio larger than 4.0. This would happen if all of the world energy was contributed by methane.

The lower curve in Fig. 4, represented by the green triangles, shows the effect on the H/C ratio if a coal economy was to prevail. This outcome is probably unlikely given the importance of striving for a healthy environment without high carbon dioxide and other greenhouse emissions.

The curve made of red full circles in Fig. 4 represents the contribution of a possible future hydrogen economy to the world, as calculated by the GEM model. The best fit is obtained by matching directly the historical data and then using the matching results to forecast H/C ratios to the year 2100. The difference between the red circles and blue crosses would be the actual hydrogen contribution, which would lead to a sustainable economy. As the H/C ratio becomes larger, the carbon contribution becomes smaller. This is the energy revolution foreseen by Vaitheeswaran (2003) that "will transform an industry, change our lives and maybe even save the planet." Or as stated by Hefner (1999) "as the Age of Energy Gases advances, together with the continuing revolutionary changes in communications, information transfer and education, the world economies will become increasingly globalized and capable of sustaining economic growth while enhancing the global environment. Our future is bright!"

Forecasts are never met precisely and the same holds true for the ones presented in this article. Changes in technology and the triple bottom line (economic, environmental, and social issues) can have very quick impacts on any forecast. Although the past is not always an indication of the future, the good fits for historical data presented in this study lead us to the conclusion that the GEM model can be used cautiously for examining possible future outcomes and opportunities. The resources available (oil, gas, and natural gas liquids) in our planet are very large and should take us, with proper planning and R&D, to the next dominant economy.

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