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World Natural Gas Endowment as a Bridge towards Zero Carbon Emissions

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ABSTRACT

We use a global energy market (GEM) model to show that natural gas has the potential to help stabilize global carbon emissions in a span of about 50-100 years and pave the way towards low and zero carbon energy.

The GEM provides a close fit of the global energy mix between 1850 and 2005. It also matches historical carbon and CO_2 emissions generated by the combustion of fossil fuels. The model is used then to forecast the future energy mix, as well as the carbon and CO_2 emissions, up to the year 2150.

Historical data show relative decarbonization and an increase in the amount of hydrogen burned as a percent of fossil fuel use between 1850 and 1970. The GEM indicates that with a larger contribution of natural gas to the future energy market, the burned hydrogen percentage will increase. This decarbonization will help to advance economic and environmental sustainability.

Keywords: Natural gas; Energy Mix; Emissions; Decarbonization

1. INTRODUCTION

Energy services are a vital need and are indispensable for human well-being. Significant

challenges exist, ranging from energy security to environmental quality. Historically,

economic growth has been primarily fuelled by coal and oil. As the world economy

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continues to expand over the long term, natural gas has the potential to play a significant role in satisfying energy demand and acting as a bridge towards renewables *(1)*. Increased use of gas will help to reduce dependency on oil and coal, which may result in increased energy security and reduced environmental impact. Thus, the aim of this paper is to analyze the role of natural gas, on a global scale, in providing a sustainable global energy future. In particular, this paper provides projections related to natural gas and its association to the energy mix, decarbonization, and carbon emissions.

The themes of this paper support the work of experts visualizing a bright future for natural gas as a transition fuel *(e.g. 1-7)*. Common forecasting models for estimated energy demand include IEA MARKAL *(8)* and the IAEA MAED *(9)*. For a comparative study of energy demand models, see *(10)*. Reserve estimates are presented annually in the British Petroleum Statistical Review of World Energy *(11)* and by the U.S. Energy Information Administration *(12)*. Estimates of resources are periodically assessed by the United States Geological Survey *(13)* and the German BGR *(14)*.

Recent natural gas estimates indicate marketable resources of 2,074 tcf in the United States *(15)*, and 700 to 1,300 tcf in Canada *(16)*, are much larger than previously assessed. The same holds true for the world when natural gas in conventional, tight, shale and coalbed reservoirs is taken into account *(17-18)*.

The endowment in these four types of reservoirs is estimated at 45,000 trillion cubic feet (tcf) split into 15,000 tcf in conventional reservoirs; 15,000 in tight gas reservoirs; 10,000 in shale gas reservoirs; and 5,000 in coalbed reservoirs.[1]

Endowment refers to the sum of known volumes of hydrocarbons (cumulative production plus remaining reserves) and undiscovered volumes *(13)*. We estimate that cumulative gas production for the world until 2005 is approximately 2,776 tcf. Thus, the 'future endowment' (i.e. endowment minus cumulative production) suggests that at current rates of natural gas production of 106 tcf/year *(11)*, the resource would last for 398 years. **Table 1** presents a summary of alternative conventional and unconventional fossil endowments and the time they would last depending on various assumed production growth rates.

Table 1 – Life expectancies

1	2	3	4			5
Commodity	Future [a] Volumes	2007-2009 [b] Average Annual Production	Life Expectancy in Years, at Various [c] Growth Rates in Production			Average Annual [d] Growth in Production, 1979-2009 (%)
			0%	2%	5%	
Conventional Gas, Tight Gas, Shale Gas, Coalbed	4.22E+16	1.06E+14	**398**	**110**	**61**	2.51
Conventional Oil	3.50E+12	2.96E+10	**118**	**61**	**39**	0.67
Heavy Oil, Oil Sands, Oil Shale	2.30E+13	2.96E+10	**777**	**140**	**74**	-

Notes:

a. Conventional oil, heavy oil, oil sands and oil shale in barrels; conventional gas, tight gas, shale gas and coalbed in cubic feet

b. Average annual production comes from British Petroleum (2010)

c. Life expectancies estimated by this study

d. Average annual growth in production calculated from British Petroleum (2010)

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[1] GFREE research team, Schulich School of Engineering, University of Calgary, Canada. GFREE is a target-oriented research program developed in attempts to increase natural gas rates and recoveries from low permeability formations. The program uses an integrated approach that includes geoscience (G), formation evaluation (F), reservoir drilling, completion and stimulation (R), reservoir engineering (RE), and economics and externalities (EE).

In addition to more comfort and convenience, the large gas endowment can help pave the way towards environmental sustainability. As we demonstrate, natural gas use could help stabilize carbon and CO2 emissions within 50 to 100 years and eventually lead to a zero carbon energy economy in which renewables dominate the energy mix.

2. THE GLOBAL ENERGY MARKET (GEM) MODEL

The GEM model is based on a previous logistic substitution model that provided a good match of the energy mix from approximately 1850 to 1970 *(19-20)*. After 1970, the actual historical data deviated from the logistic model. The GEM model takes this deviation into account while providing a good fit of all the historical data.

Figure 1 shows world primary energy consumption and substitution starting in the year 1850. The black curves correspond to actual historical data taken from *(21)*. The color symbols represent the best fit using theoretical values calculated with the GEM model, which is based on a binary technology substitution model given by *(19-20)*:

$$\frac{f}{1-f} = \exp(\alpha t + \beta) \qquad (1\text{-}1)$$

where f is market share of a competitor, t is time, and α and β are parameters. Fisher and Pry define y_{FP} as,

$$y_{FP} = \frac{f}{1-f} \qquad (1\text{-}2)$$

Equation 1-1 indicates that a semilogarithmic plot of y_{FP} versus time should result in a straight line with a slope equal to α and intercept equal to β. We modified equation 1-1 when we observed deviations from the straight line for the energy sources discussed in this study. The deviations included slight or severe increases or decreases in f. We handle the deviations empirically by incorporating a severity exponent, S, and a parameter, ψ, in equation 1-1 *(22)*. The modified equation takes the form *(23)*:

$$y_{AA} = \frac{\exp(\alpha t + \beta)}{\psi + (1-\psi)\left[1-\exp\left(-\dfrac{y_{FP}}{y_{CO}}\right)\right]^{S}} \qquad (1\text{-}3)$$

where y_{CO} is a constant determined from the match of the historical data and the theoretical energy fraction is given by:

$$f = \frac{y_{AA}}{1 + y_{AA}} \qquad (1\text{-}4)$$

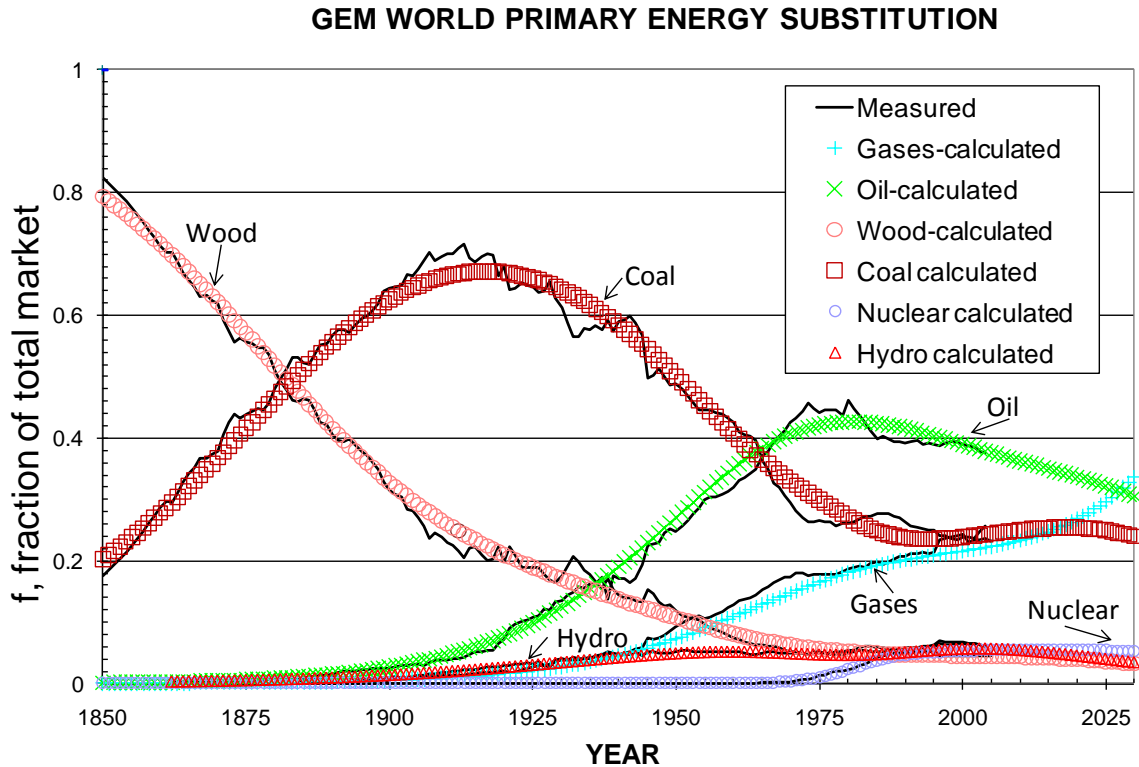**GEM WORLD PRIMARY ENERGY SUBSTITUTION**

Figure 1 - World substitution curves from the GEM model including wood, coal, nuclear, hydro, oil and gases *(23)*.

As an example, the filled magenta squares in **Figure 2** show [$f / (1 + f)$] values of the measured contribution of natural gas to the global energy market versus time. Time zero in the lower horizontal scale corresponds to the year 1850 (shown in the upper horizontal scale). The measured data form an approximate straight line starting in 1906 (56 years in the lower scale) that deviates from linearity around 1968 (118 years in the lower scale). From the straight line, the values of α and β are determined to be approximately 0.057 and 8.1, respectively. Other parameters are determined from the trend that deviates from linearity, and are as follows: $\psi = 0.052$, $y_{co} = 3.61$ and $S = 1.30$. Finally, the fraction f is calculated from equation 1-4 and is plotted in **Figure 2** (shown by the symbol 'X').
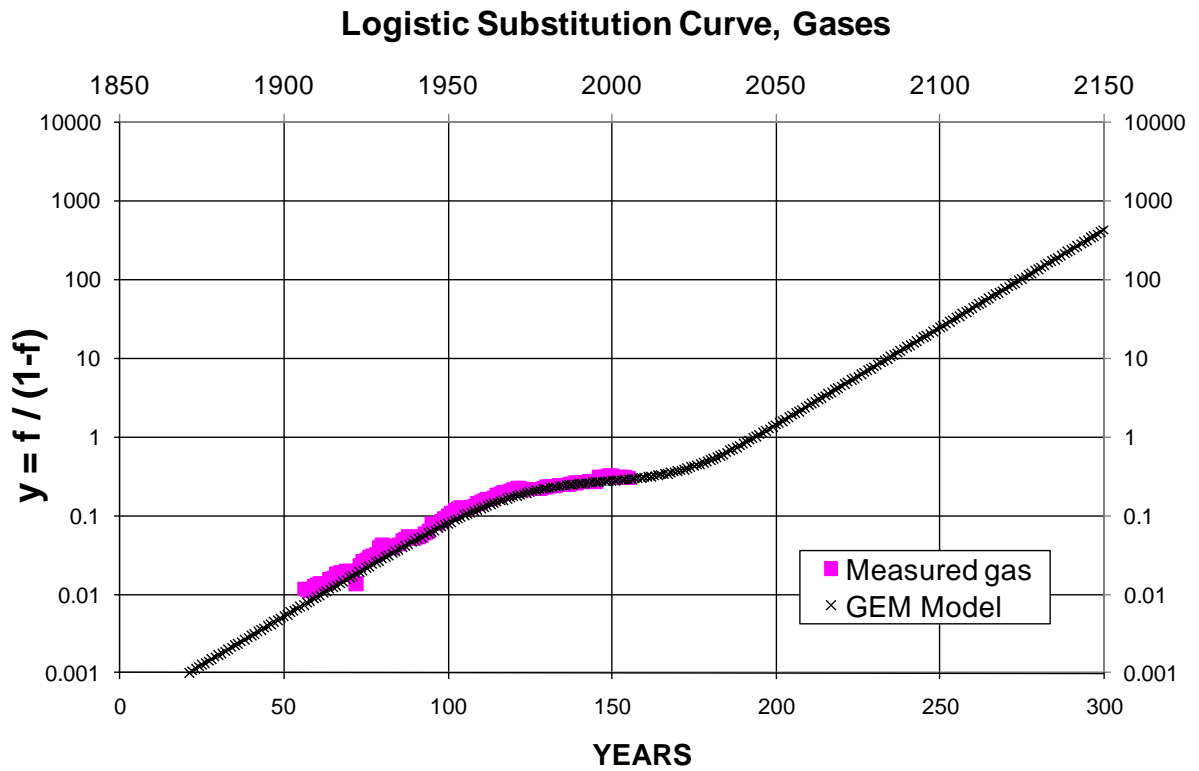
Logistic Substitution Curve, Gases

Figure 2 – Use of GEM model for matching historical contribution of natural gas to the global energy market.

3. RESULTS

Returning to **Figure 1,** we see that in 1850, wood, agricultural residues and animal dung

contributed approximately 80% of the total energy market while the share of coal was in

the order of 20%. This was followed by a significant increase in coal consumption that

reached a peak around 1912, with a contribution of about 70%. At this point, the market

share of wood and other solids had decreased to about 22%.

The oil industry was born in the late 19th century and soon oil was contributing about 7% of the total energy market. The oil share peaked in the 1970s with a contribution of about 50% and would never reach the heights of coal. By that time, the natural gas industry was developing and reached a market share of about 18%. The share of coal had been declining continuously and in the 1970s stabilized at about 28%. The 4% balance was composed mostly of hydroelectricity and nuclear energy.

More recently, the contributions of coal and natural gas have been at about 29% and 24%, respectively, with oil providing approximately 35% and the balance being contributed by hydroelectricity, nuclear, wind and other minor sources of energy.

Figure 1 also presents a GEM forecast showing that the natural gas share of the global market will continue to increase and reach about 33% by the year 2030. On the other hand, the graph also shows that the percent contribution of oil will decrease while that of coal will remain approximately constant. Increased gas penetration in the short term would mostly be found in the electricity sector. In the long term, possibilities may also exist in the transport sector. The increases in gas use could come from policies to address climate change, which are likely to favour gas in place of oil and coal. Some of these policies include indirect taxes on fuel and costs imposed on carbon emissions. By introducing a substantial cost on carbon, for example, the total cost of coal and gas becomes comparable, in which case relative prices determine the dominant fuel.

3.1 RELATIVE DECARBONIZATION OF THE ENERGY MARKET

The significant increases in the endowment of natural gas reported recently *(15-18)* provide an ideal opportunity to decrease the relative carbon emissions that result from the burning of fossil fuels. This is illustrated in **Figure 3**, which shows the GEM best fit of the historical hydrogen and carbon burned as a percent of fossil fuel consumption since 1850.
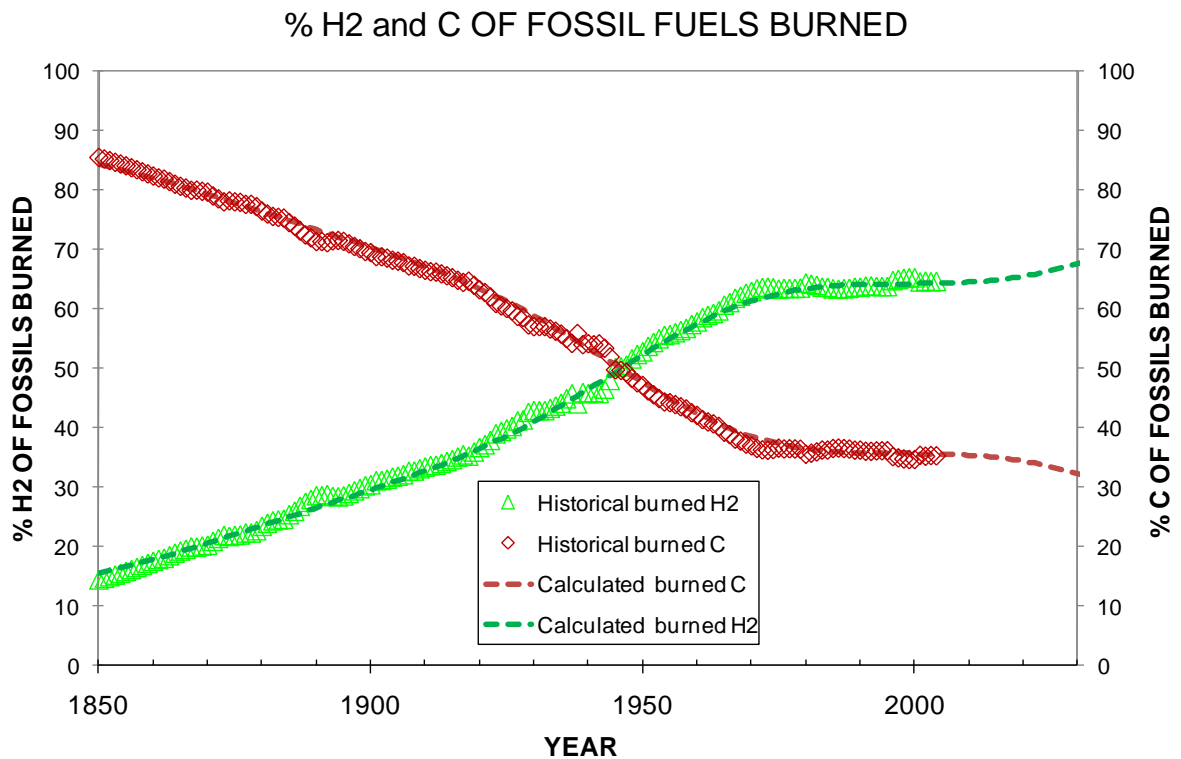

Figure 3 – Percent hydrogen and carbon of fossil fuels burned worldwide.

The calculation of the hydrogen percentage of fossil fuels burned is carried out using the actual (measured) and calculated fractions of wood (including animal dung and other

agricultural residues), coal, oil and gas shown in **Figure 1**. Also, the following average

H/C ratios are used: wood 0.10, coal 0.5, oil 2.0, and gas 4.0 *(3)*. For example, in the year

2004, the percentage of the total market contributed by wood (including animal dung and

other agricultural residues) was 4.6%, coal 25.7%, oil 37.5% and natural gas 23.6%.

Thus the overall H/C ratio was 0.046*0.1 + 0.257*.5 + 0.375*2 + 0.236* 4 = 1.827. The

percent of hydrogen burned was 1.827 / (1+1.826) = 64.6%. The balance (35.6%)

represents the carbon burned. The comparison of actual and calculated burned

percentages is good, with an R^2 equal to 0.99.

As seen in **Figure 3**, the percent of burned hydrogen - a proxy for environmental quality -

has been increasing continuously from 15% in 1850 to approximately 64% at present,

with the balance of 36% going to carbon. Beginning in 1970, the hydrogen burned

becomes approximately constant at about 64% and has since remained at the same level.

By the year 2030, the burned hydrogen will have increased to approximately 68%, with a

corresponding decline in carbon to 32%.

3.2 ACTUAL CARBONIZATION OF THE ENERGY MARKET

Although the relative decarbonization illustrated in **Figure 3** is important and

meaningful, the fact is that actual volumes of carbon emissions to the atmosphere since

1850 have increased substantially, as shown in **Figure 4**. Thus, in reality there has been

an actual carbonization of the global economy, rather than decarbonization.

GLOBAL FOSSIL CARBON EMISSIONS
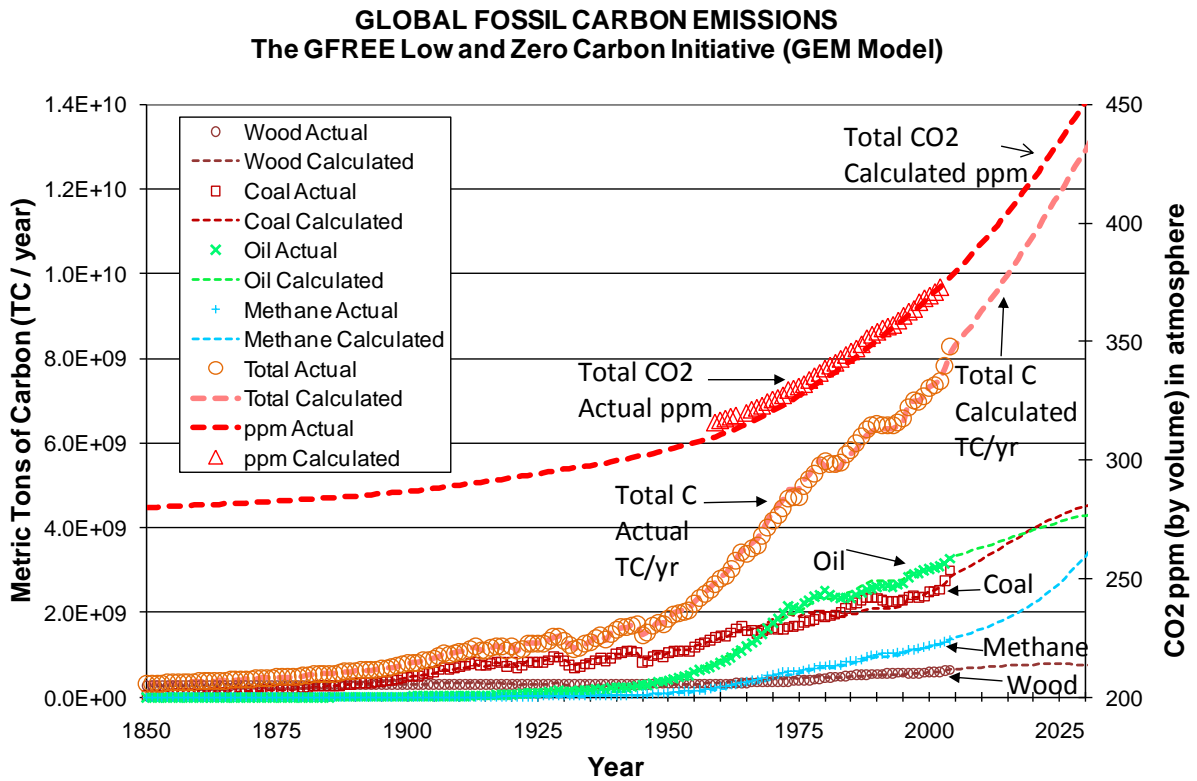**The GFREE Low and Zero Carbon Initiative (GEM Model)**

Figure 4 – Actual and best fit global fossil carbon and CO2 emissions.

The graph in **Figure 4** includes individual curves of carbon production from wood (and other solids), coal, oil and natural gas, and the CO2 equivalent of the total emissions. The dashed curves represent actual data and the color symbols correspond to GEM-calculated carbon and CO2 values, which fit the actual data very well with coefficients of determination (R^2) greater than 0.98 in all cases. **Figure 4** shows that at present the larger carbon contribution is provided by oil and coal, followed by natural gas (methane). The amount of carbon resulting from burning oil, for example, amounted to 3.27E9 metric tons per year in 2004. The amount is calculated as the product of the fraction of the total

market contributed by oil (0.375) times total energy consumption (4.19E9 tons of oil equivalent) times the effective fraction oxidized (0.918) times carbon content in tons per ton equivalent of crude oil (0.85). Similar approaches are used for other contributors to the global energy market. Their summation gives the total carbon for 2004, as shown in **Figure 4**. The curve at the top of the graph (CO_2 emissions in ppm by volume in the atmosphere) is calculated from the cumulative of the carbon emissions divided the grams of CO2 in a gram of carbon. For example, the cumulative carbon emissions by 2004 were 8.15E9 metric tons. This is converted to grams and divided by 3.664 grams of CO_2 per gram of carbon. As the calculation is started in 1850, we add the estimated CO_2 in the atmosphere at that time (280 ppm) to the result of the previous calculation.

As seen in **Figure 4**, total carbon emissions have increased dramatically since 1950 and at present stand close to about 8.5 billion metric tons of carbon per year. The GEM model forecasts that carbon production will increase to about 13 billion metric tons per year by 2030. This is equivalent to an increase from approximately 384 ppm of CO2 by volume in the atmosphere at present to about 450 ppm of CO2 by volume in 2030. Based on our analysis, the large amounts of carbon can be stabilized within the next 50 to 100 years and eventually be reduced as low and zero carbon energy sources are able to meet the needs of society.

3.3 LOW AND ZERO CARBON INITIATIVE

To accomplish the carbon reductions mentioned above, society would have to take advantage of the vast amounts of available natural gas in conventional, tight, shale and coalbed reservoirs. Using the fit presented in **Figure 1,** we have generated a production forecast showing the contribution of different sources of energy to the year 2150, as shown in **Figure 5**.
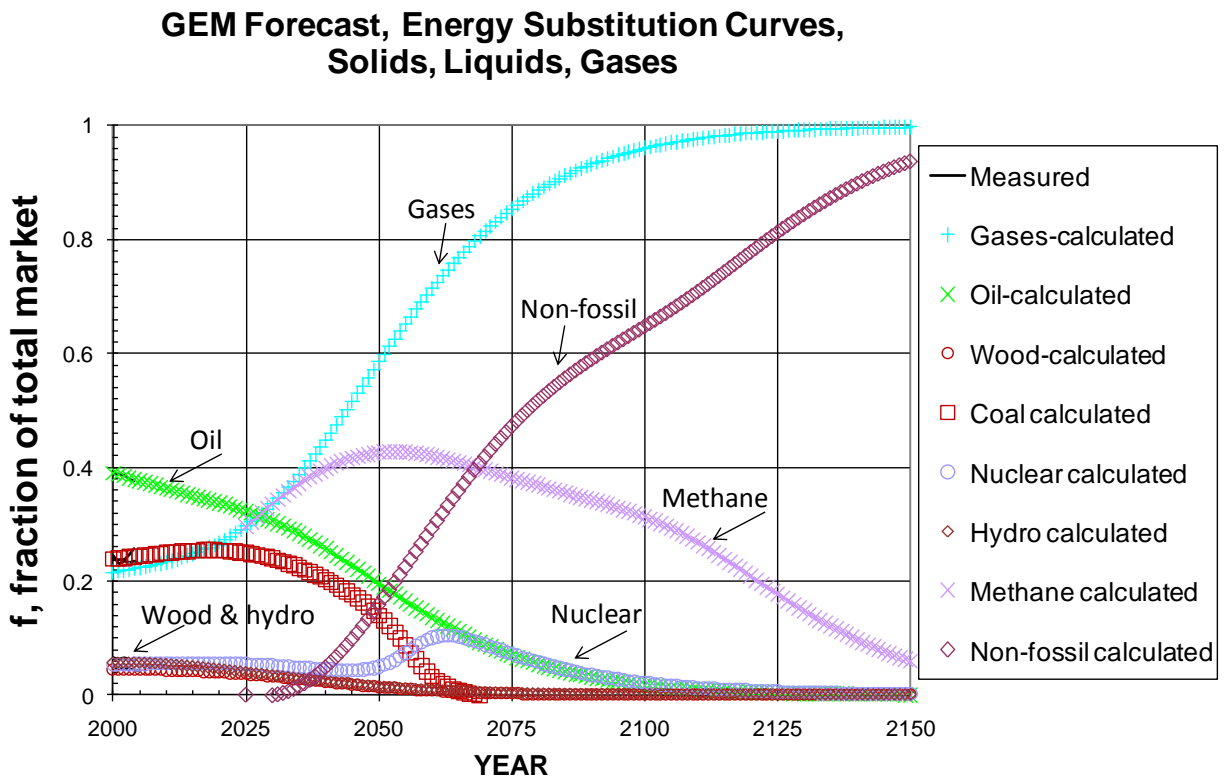
GEM Forecast, Energy Substitution Curves, Solids, Liquids, Gases

Figure 5 – Forecast substitution curves. Black lines between 2000 and 2010 correspond to the best fit shown in Figure 1.

This forecast assumes that the fraction of the total market contributed by natural gas will resemble the cycle contributed by oil. The latter started in the late 1800s and would end in the early 2100s, not because of lack of oil resources but because of substitution to more environmentally benign sources. A scenario from the GEM model shows that within the next few years the coal share of the energy mix will not increase much more than at present (about 29%) and will start to decrease significantly and definitively around 2030. As governments force producers to pay for external costs of fossil fuel production, this will increase the relative price of coal while encouraging investment in gas, which would lead to technological improvements in gas exploration, production and transportation. This would further induce substitution from coal towards gas by lowering the relative price of gas.

The natural gas cycle contribution to the total global market would reach a peak around 2050-2060 and then would start to decline, as shown in **Figure 5**. The availability of natural gas would allow for the necessary time to develop non-fossil, renewable sources.

Figure 6 shows a forecast of carbon emissions from the year 2000 to 2150. The actual data points starting in the year 2000 are taken from **Figure 4**. The forecast is performed using the best fit parameters estimated for **Figure 4.**

GLOBAL FOSSIL CARBON EMISSIONS
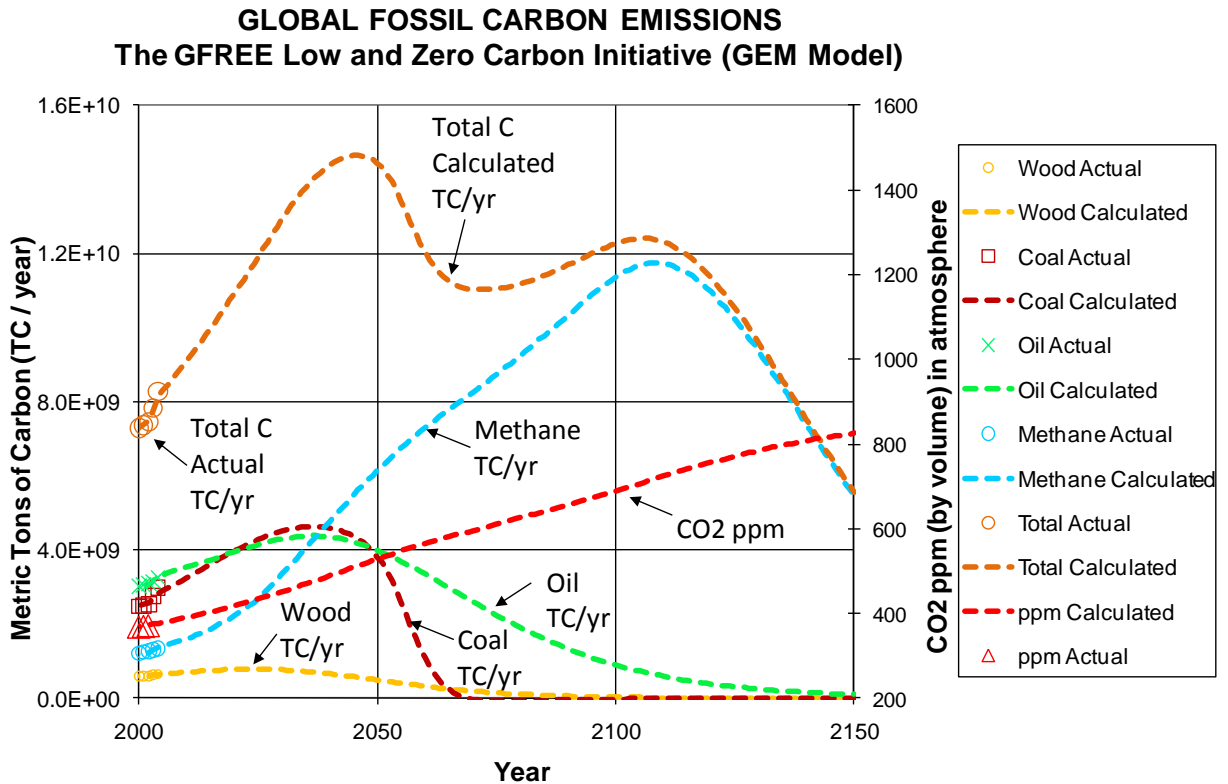**The GFREE Low and Zero Carbon Initiative (GEM Model)**

Figure 6 – Forecast of global fossil carbon emissions. The global carbon peak would occur around 2040-2050 with the proposed initiative.

The curves in **Figure 6** suggest that carbon contributions by oil and coal would continue

to increase and reach a peak around 2040. Just a few years later, the summation of

carbon emissions from all sources would reach a maximum. Carbon from natural gas

would continue to increase until reaching a peak around 2110.

The overall forecast becomes favorable around 2050 as carbon emissions start to

decrease. There is a second peak at a lower level around 2110. That is the point where

carbon production per year starts a definitive decline, as seen in **Figure 6**.

Notwithstanding that natural gas is the cleanest burning fossil fuel available, it is clear from **Figure 7** that natural gas production would generate a significant amount of carbon emissions that would surpass those of oil and coal around 2030 and reach 1E11 metric tons of carbon per year by 2150. Thus, a transition to non-fossil energy sources, as seen in **Figure 5**, would be necessary in order to decrease carbon emission levels to those of **Figure 6**. Possibilities for significant future contributions to the mix would come from a combination of wind, solar, biofuels, water and hydrogen. Hydrogen, an energy carrier, can be generated from natural gas but eventually would have to be produced from non-fossil matter. The possibility of massive and economic generation of hydrogen is being studied by various research teams *(24)*.
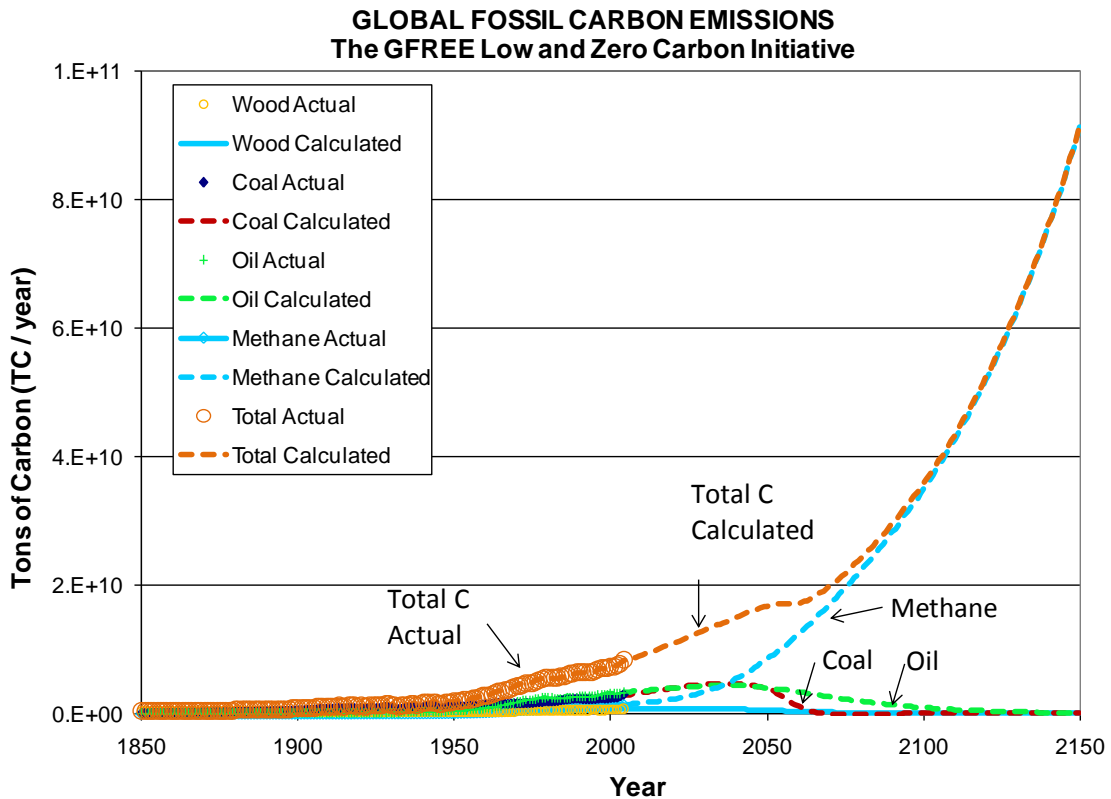

Figure 7 – Even if methane becomes the only source of energy to meet global needs, still the carbon emissions would grow to almost 1E11 metric tons per year by 2150.

4. DISCUSSION

The GEM projection shown in Figure 1 indicates that the share of natural gas in the future energy mix will increase. However, progress in the natural gas industry will not occur autonomously over time. The effects of energy policy and technology advancement will be critical to develop the large natural gas endowment. Governments must create incentives to produce and deliver abundant conventional and unconventional gas resources to the marketplace. For instance, increases in gas use could come from stringent policies to address climate change, which are likely to favor gas in place of oil and coal. Some of these policies include indirect taxes on fuel and costs imposed on carbon emissions. By introducing a substantial cost on carbon, for example, the total cost of coal and gas becomes comparable, in which case relative prices determine the dominant fuel. Presumably this would increase the relative price of coal while encouraging investment in gas, which would lead to technological improvements in gas exploration, production and transportation. This would further induce substitution from coal towards gas by lowering the relative price of gas.

Similarly, policies will be important in continuing the improvement of the hydrogen over carbon ratio. Figure 3 shows that the percentage of burned hydrogen is likely to increase in 2030 and beyond. However, there must be increased understanding of the actions that encourage or discourage natural gas use. Society may be forced to revert to an intense use of coal if policies are adopted that hinder the penetration of gas into the market place (and thus reduce the percentage of burned hydrogen relative to burned carbon). Government

regulations such as price setting have the effect of keeping natural gas prices artificially low. These low prices do not provide incentives for companies to invest in the upstream, midstream, or downstream segments of the industry. Increased coal subsidies further hinder the penetration of gas into the market. Policies that limit new entry and foreign investment (either through high taxes and royalties or resource nationalization) will also inhibit the contribution of gas to the energy market.

As seen in Figure 4, total carbon emissions have increased substantially since 1950 and will still be increasing in 2030 due to intensive use of fossil fuels. However, the combination of fossil fuels over the next several decades remains uncertain and will depend heavily on the choices made by governments, corporations and consumers.

Although we have indicated that natural gas is abundant and may allow for the necessary time to develop non-fossil, renewable sources (Figure 5), technical and market research is still needed in the gas and renewables industries. For example, will international gas markets develop sufficiently to stimulate development of shale gas outside the United States and Canada? Will best practice in hydraulic fracturing be achieved around the world to alleviate the fears of associated environmental impacts? Will technology advance enough to reduce the costs of renewable such that they will be cost effective? Questions like these, as well as results from this study, should help inform and drive future research. The carbon emission peak occurring around 2040-2050 (Figure 6) will further depend on the successful development of non-fossil energy sources such as

hydrogen and renewables. Again, the technical and commercial viability of these sources will require large amounts of investment in research and development.

5. CONCLUSION

This study assesses the impacts of competing fuels in the energy mix and finds that natural gas use has the potential to help significantly in the reduction of carbon emissions while increasing economic growth. In addition, increased natural gas use has the potential to fortify regional and international trade relations while ensuring energy security. These themes are important due to the significant global economic and environmental implications.

The GEM model has provided a very good fit of the historical mix of energy sources, including wood (and other solids such as agricultural residues and animal dung), coal, oil, natural gas and other minor sources. The model is also accurate in matching historical carbon and CO_2 emissions generated by the combustion of fossil fuels. These validations provide the basis to make forecasts of the energy mix, and carbon and CO_2 emissions, to the year 2150. Given appropriate energy policy and sufficient technological progress, we find that intensive use of natural gas will help stabilize carbon emissions starting within the next 50 to 100 years. We also anticipate that meeting energy needs with natural gas will allow for the necessary time to develop non-fossil energy sources. As a result, carbon emissions will start to decrease in a definitive way in approximately 100 years. The main

limitation of the GEM model at present is that its results are contingent on the enactment of policies that encourage the development and consumption of natural gas as well as renewables.

The recent significant additions to the endowment of 'conventional' natural gas in the form of gas from 'unconventional' tight, shale and coalbed reservoirs (and potentially gas hydrate reservoirs) suggest that unconventional gas formations could also provide a significant contribution in meeting global energy demand - estimated at approximately 722 quads by 2030 *(23)*. However, a large unconventional gas endowment does not necessarily imply that gas will capture increased market share in the future and help in the transition towards environmental sustainability. Government regulation has a major role to play in determining the future of unconventional gas. For instance, effective regulation of shale gas production will help mitigate risks such as excessive water use, contamination and disposal.

Additional questions about the long term commercial viability of unconventional fossil fuels and non-fossil alternatives remain unanswered. Thus, future research will include analysis of the total economic cost, including environmental and social costs, of unconventional gas and renewable energy production. The feasibility of renewables, as well as gas as a transition fuel, depends in large part on technological advancement that would lower total production costs over time. Ongoing research into massive and economic generation of hydrogen as an energy source must continue as well.

ACKNOWLEDGEMENTS

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VITAE

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