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ORIGINAL PAPER

Revisiting the role of natural gas as a transition fuel

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Abstract

The objective of this paper is to assess the potential of natural gas as a transition fuel towards a low- and zero-carbon economy. We use the previously established global energy market model (GEM) to first provide a close match of the historical energy mix and the associated carbon levels. The model is then used to make simulations of how the energy mix and carbon quantities would evolve in the long distant future—the year 2150—if past dynamics were an indication of the future. A similar GEM modeling exercise was carried out in a previous work, using historical data up to the year 2005, showing that natural gas would help slow global carbon growth in the next 50–100 years, thus paving the way towards a low carbon future dominated by non-fossil energy use. The present study uses the most recent statistics, from 2005 to 2017, to verify the accuracy of the original GEM projections. Our findings show continued penetration of natural gas in the energy mix until the mid-twenty-first century and an eventual reduction of carbon levels starting around that time.

Keywords Natural gas · Bridge fuel · Transition · Energy mix · Carbon · Emissions

Introduction

Our paper proceeds as follows: This introductory section elaborates on the expectations for natural gas in the future. In Section 2 we briefly describe the Global Energy Market model (GEM). Section 3 examines historical decarbonization and provides projections of future decarbonization to the year 2040. Section 4 extends the vista with a projection of the energy mix and the corresponding carbon output to the year 2150. Section 5 discusses our results in the context of policy and technological efforts to stabilize climate.

Expectations for natural gas

In the past half century, pollution and the environment has emerged as one of the dominant concerns in the public discourse about threats to humanity (Tilton and Guzmán 2016). As the world economy continues to expand over the long run, it has been argued that natural gas could play a significant role in satisfying energy demand and provide a bridge for largescale renewable energy use (Aguilera and Aguilera 2012; Hefner III 2009, among others). In contrast, some research casts doubt on the importance of gas as a transition fuel, given that it is a fossil fuel (e.g., Howarth 2014).

In the short run, increased gas use will mostly be found in electricity generation, as there is potential for gas to take market share from coal in that sector, particularly in emerging Asia. In the long run, some possibilities are likely to exist in the transportation sector—where natural gas can compete with oil.

The rapid growth of gas consumption in past decades is based on its many benefits relative to other fossil fuels: its wide geographical distribution, its affordability, and its environmental benefits (given the lower carbon intensity of gas compared with coal and oil). In addition, there is an abundance of gas resource endowments around the world. Apart from the vast conventional gas resources, there is potential for unconventional sources including tight gas, shale gas, and coalbed methane.

In 2017, the contributions of coal and natural gas to the energy market stood at 28% and 23%, respectively, with oil at approximately 34%, and the balance of 15% consisting of hydroelectricity, nuclear, wind, and other minor sources (BP, annual).

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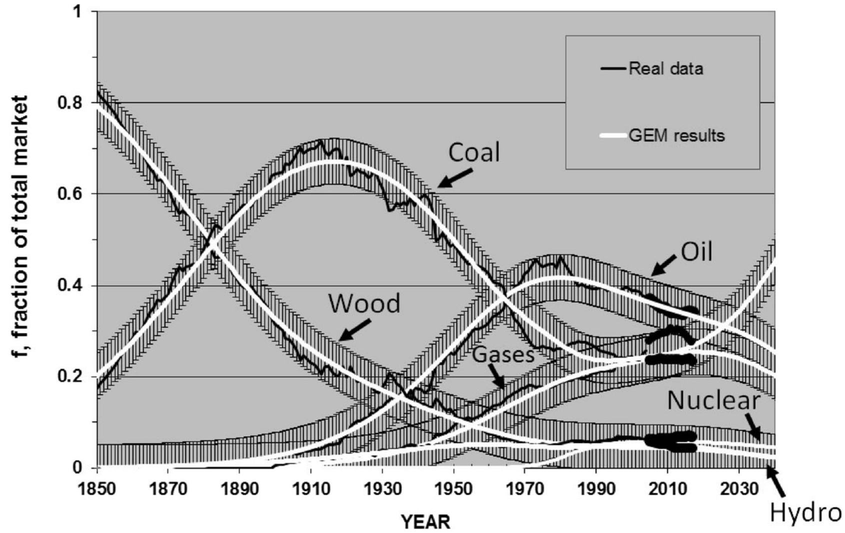

Fig. 1 GEM curves generated in 2007 versus real data for wood, coal, nuclear, hydro, oil, and gases. Recent data (covering 2005–2017) from BP (annual) is represented by fat black markers. Vertical error bars (5%) highlight good quality of the historical match (adapted from Aguilera and Aguilera 2018)

The GEM model adds to the existing literature on the energy mix but employs a unique methodology (see next section), in that, we start by observing the curvature on a graph given by the historical market share of each energy resource over time. We then develop the GEM which allows the data to determine the specified shapes of the curves. Next, the model is extended out of sample in order to make projections for the future. The close match of the historical data, generated by the GEM, provides some confidence that the estimates of the future are reasonable. Moreover, the baseline energy mix scenario remains unaltered since its creation in 2007, and the projection has proven accurate when compared with data from the last 10 years (Aguilera and Aguilera 2018). This contrasts with the work of other organizations, who revise energy mix projections annually based on the latest changes in investments, policies, and other variables.

Figure 1 displays past energy mix data from 1850 to 2017. In addition, it shows an excellent historical match provided by the GEM (Aguilera and Aguilera 2018)—the GEM curves are developed with Eq. 2 and its variations, as presented in the next section. The figure also provides a projection to the year 2040, where gases—mostly in the form of methane, but also some solar, wind and hydrogen[1]—have a clear lead in the energy market by that time. The validation of the GEM with data from the last 10 years, and the good fit with the preceding history, suggests the projections could be used with a reasonable level of assurance to inform the enactment of public policy.

[1] The concept of including those renewables in the *gases* category was introduced by Hefner III (2002, 2009) and was explained as follows: "The Earth's atmosphere is a gas and wind is driven by the Earth's daily heat from the sun. The sun is mostly burning hydrogen gas and each day the Earth is bathed in virtually limitless solar energy."

Global energy market model

Details of the GEM model, which estimates the fractional contribution of different primary energy sources over time to the global market, have been published in several previous works (Aguilera and Aguilera 2007, 2008, 2012, 2018). Thus, the present paper provides only an abridged description of the model.

The GEM is based on a model of binary technology substitution given by Fisher and Pry (1970), later used by Marchetti and Nakicenovic (1979):

$$y_{FP} = \frac{f}{1-f} = \exp(\alpha t + \beta) \tag{1}$$

Where:

y_{FP} is an exponential function;

f is the market share of a fuel, measured as a fraction of total energy consumption;

t is time;

α and β are constants.

The Fisher and Pry model states that if $y_{FP} = f/(1-f)$, 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. This standard logistic substitution model would give a good match of the historical energy mix data from 1850 to about 1970—coal's share had been in steady decline for decades while the gas share was continually rising. After 1970, the actual data would deviate from the model, due to suddenly intensive coal use that helped the fuel re-capture market share, particularly in Asia.

We modify Eq. 1 and introduce some new parameters to include the effects of the deviation from linearity (Aguilera and Aguilera 2007, 2008). As seen in Eq. 2, there are five parameters in the GEM that are estimated with non-linear

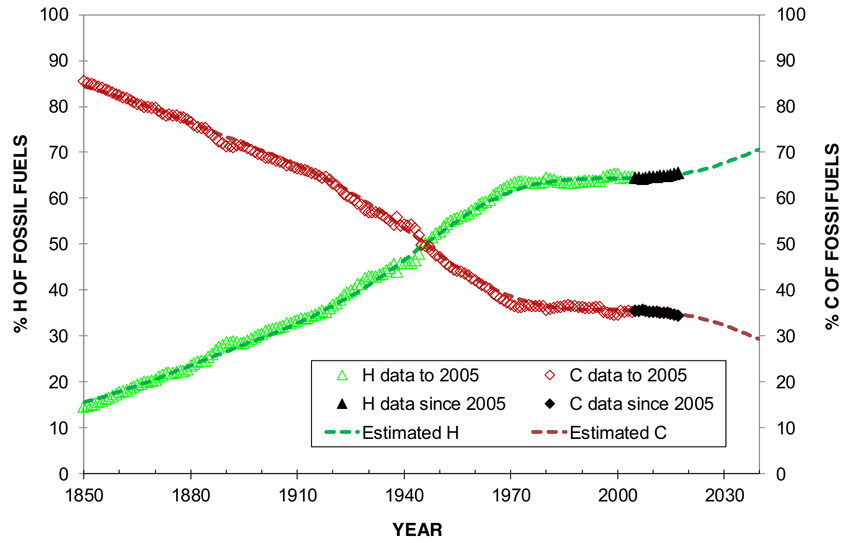

Fig. 2 Percentage of burned hydrogen and carbon worldwide. Curves show overall environmental quality improvement. GEM provided good match of actual data between 1850 and 2005 (Aguilera and Aguilera 2012). Validity of original projection tests favorably against recent data, covering 2005–2017 (BP, annual), represented by black markers

regression to give the best possible match of the historical energy mix data—from 1850 to 2017. Using the estimated parameter values, the model can then be extended into the future.

As presented in Eq. 2, the GEM model is used to calculate the market fraction of an energy source that is generally declining with time (e.g., solids like wood and coal):

$$y_{GEM} = \frac{\exp(\alpha t + \beta)}{\psi + (1-\psi)[1-\exp(-y/y_s)]^S} = \frac{f}{1-f} \quad (2)$$

Where:

y_{GEM} is our modified function;

α, β, t, and f are defined above for the Fisher and Pry model;

y_s is an estimated parameter to control the divergence from the original straight line;

ψ is an estimated parameter representing the approximate point at which a shifted straight line is developed;

S is an estimated parameter (we refer to it as a severity exponent) that controls the slope of the curve that diverges from the straight line;

y is a standard logistic substitution function, like that in Eq. 1.

For an energy source with a market fraction that is generally increasing with time (e.g., gases), the numerator in Eq. 2 is multiplied by ψ, as defined above. The parameters for each curve are not equal and have to be determined independently for each case.[2] The market fraction of the liquids is calculated as the difference between 1.0 and the summation of the solids and gases fractions.

[2] For gases, the parameter values generated by the model are as follows: $\alpha = 0.057$, $\beta = -8.1$, $\psi = 0.052$, $y_s = 4$, and $S = 1.3$. For the solids, they are $\alpha = -0.0519$, $\beta = 5.6278$, $\psi = 0.029$, $y_s = 0.25$, and S = 1.6.

The accuracy and simplicity of this approach, which can be easily reproduced, is meaningful when considering the complexity and volatility of world energy markets. The GEM findings can also be used to calculate carbon levels over time, as described in the sections that follow.

Decarbonization: history and prospects

Carbon use has increased substantially since 1950 and is expected to keep rising for decades due to ongoing consumption growth of fossil fuels. However, the combination of fossil fuels over the long run, and thus the level of carbon, remains uncertain and will depend heavily on the choices made by governments, corporations, and consumers. Significant increases in the endowment of natural gas reported in recent years (e.g., EIA/ARI 2015) provide an ideal opportunity to decrease relative carbon levels in the energy system.

The GEM model has been used to match the historical hydrogen and carbon burned as percentages of fossil fuels consumed, and to make projections of each to 2040. The resulting curves are proxies for energetic and environmental quality (Marchetti 1985; Grubler 2004). They indicate the consumption of fuels containing hydrogen atoms relative to carbon atoms. As the energy system transitions to fuels with higher hydrogen over carbon (H/C) ratios, and thus lower carbon intensities, decarbonization is occurring. This signifies an improvement in the quality of energy sources, i.e., fuels that emit less CO2 when burned.

Figure 2 shows the GEM best fit curves of the historical hydrogen and carbon burned and the extension of the curves until 2040 (originally estimated in Aguilera and Aguilera 2012, to the year 2030). The calculation of the hydrogen percentage was carried out using (a) the

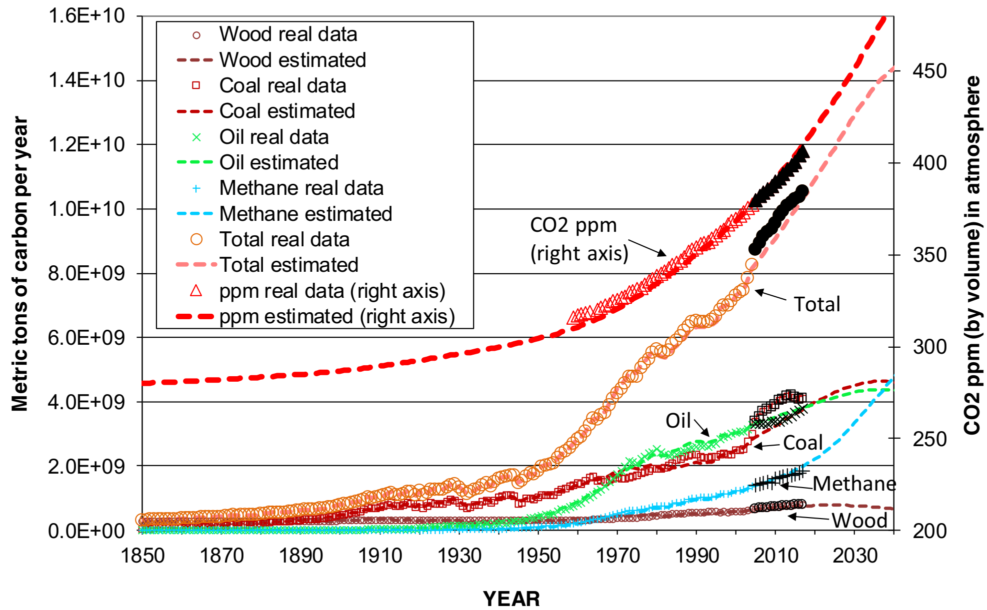

Fig. 3 Estimated global carbon versus real data. GEM provided good match of actual data between 1850 and 2005 (Aguilera and Aguilera 2012). Validity of original projection tests favorably against recent data, covering 2005–2017 (BP, annual), represented by black markers

fractional contributions to the market of wood (including agricultural residues), coal, oil, and gas (shown in Fig. 1), and (b) the following average H/C ratios: wood 0.10, coal 0.5, oil 2.0, and gas 4.0 (Grubler 2004). The latter, for example, indicates that gas contains four hydrogen atoms for every carbon atom (i.e., CH_4 or methane). According to our GEM results, in 2017, the percentage of the total market contributed by wood was 4.1%, coal 25.4%, oil 33.4%, and natural gas 26.8%. The remainder was composed of non-carbon sources. The overall H/C ratio is calculated by multiplying the market share of each energy source by its corresponding H/C ratio and then summing the results: $(0.041 \times 0.1) + (0.254 \times .5) + (0.334 \times 2.0) + (0.268 \times 4.0) = 1.871$. The percent of hydrogen burned is calculated as $1.871 / (1 + 1.871) = 65.2\%$. The balance of 34.8% represents the carbon burned.

The comparison of real and calculated data between 1850 and 2005, estimated in Aguilera and Aguilera (2012), is precise (coefficients of determination (R^2) = 0.99). In the present study, data for the years 2005 to 2017 (BP, annual) are given by black markers in the figure. Visual inspection of Fig. 2 shows that the original GEM curves are validated by the latest real data.

As seen in the figure, the percentage of burned hydrogen had been increasing continuously—from around 15% in 1850 to 65% in 1970. This relative decarbonization of the energy system corresponded to rising consumption of natural gas and a declining share of coal in the energy mix. However, hydrogen levels became approximately constant starting around 1970 and have remained roughly at the same level ever since. Hefner III (2002) asserts that government intervention in the USA (e.g., the Power Plant and Industrial Fuel Use Act of 1978) had a significant negative impact on the penetration of natural gas in the energy market. In addition, a European Council Directive from 1975 further restricted the use of gas in electrical power generation on the perception of scarcity, while policies favoring coal and nuclear were enacted (Söderholm 2001).

Looking to the future, the GEM suggests a slight improvement in the H/C ratio due to rising natural gas usage, thus helping to advance environmental and economic sustainability alike. By 2040, hydrogen production will have increased to about 71%, with a corresponding decline in carbon to 29%.

Despite the relative decarbonization of the past, the fact is that volumes of carbon production since 1850 have increased substantially, as shown in Fig. 3. The graph shows individual curves of carbon from wood (and other biomass),[3] coal, oil, and methane (natural gas), as well as the total. Equivalent CO2 parts per million (ppm) in the atmosphere are also displayed. Marker symbols represent actual data and the dashed curves correspond to GEM-estimated values, which fit the actual data very well (R^2 greater than 0.98 in all cases).

The figure shows that the largest carbon contributions in recent decades came from oil and coal, followed by methane. The carbon resulting from the burning of oil in 2017, for example, amounted to 3.79E9 metric tons. It is calculated as the oil consumption in that year (4.86E9 tons of oil equivalent), multiplied by the effective fraction oxidized—used as fuel (0.92), multiplied by the carbon content in tons per ton of oil equivalent (0.85). Similar approaches are used for the other energy sources. Their summation gives the total carbon curve seen in Fig. 3. The curve

[3] Despite the inclusion of wood in Figure 3, wood burning is sometimes considered to be carbon neutral, since presumably the resulting emissions have been sequestered previously in the wood.

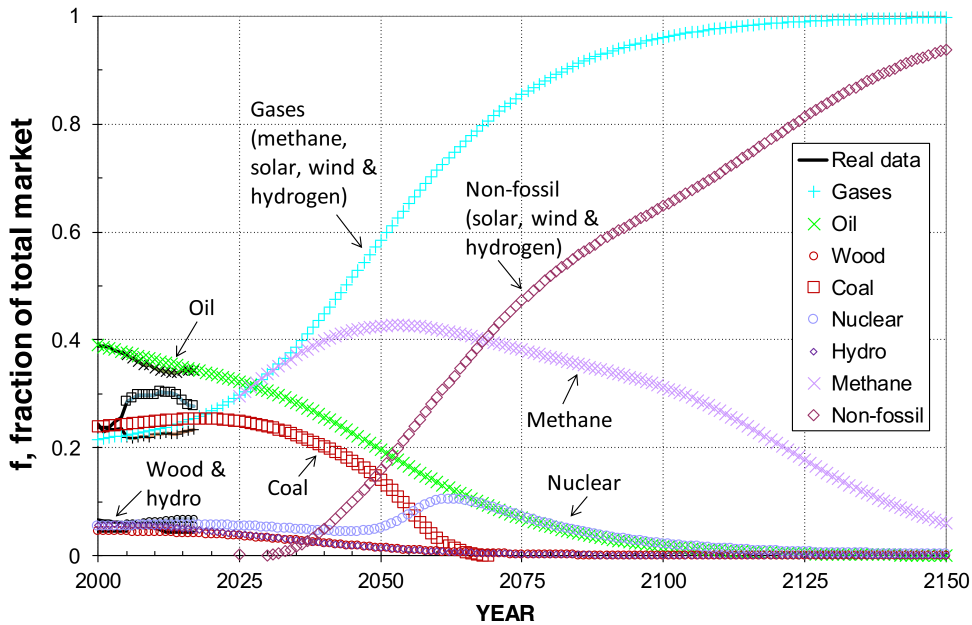

Fig. 4 Projected energy mix until 2150. Non-fossil energy becomes the market leader around 2070. Real data to 2017 (BP, annual) represented by black markers

at the top of the graph, CO2 in ppm by volume in the atmosphere, is calculated by dividing the total carbon value by the grams of CO2 in a gram of carbon (3.66).[4]

The figure reveals that total carbon levels have increased sharply from 1950 to the present. The GEM model projects that carbon production will increase to more than 14 billion metric tons per year in 2040, up from approximately 10 billion metric tons in 2017. This is equivalent to a rise from around 410 ppm of CO2 by volume in the atmosphere at present to some 490 ppm in 2040.

Energy mix and corresponding carbon in the distant future

By expanding the time horizon of the GEM-estimated energy mix shown earlier (Fig. 1), we have generated a very long-term projection showing the contribution of different resources to the market until the year 2150 (Fig. 4**)**. The scenario indicates that the fractional contribution of natural gas (methane) will resemble the cycle of oil—a gradual rise and fall in market share (with the methane peak occurring between 2050 and 2060). This will provide sufficient time to develop non-fossil sources (comprised of solar, wind, and hydrogen), which, according to the GEM results, become the market leaders around 2070. The "non-fossil" curve in the figure is estimated as the difference between the "gases" curve (generated by the GEM; includes methane and renewables) and the "methane" curve (which from 2025 is assumed to have the same fractional share as oil). As for coal, its share will not increase from much more than present levels (approximately 28%) and start a definitive decline in the mid-2020s, as seen in the figure.

Based on these results, carbon levels could be stabilized within the next 50 to 100 years and then decline permanently, as natural gas and renewable energy consumption rises. To accomplish this, the world will have to initially take advantage of the vast amounts of available natural gas in conventional, tight, shale, and coalbed reservoirs. Aguilera and Aguilera (2012) show that physical endowments of gas from conventional and unconventional formations, totaling 45,000 trillion cubic feet, are large enough to fulfill our energy mix and carbon scenarios.

Figure 5 extends the earlier projection of carbon levels to the year 2150. The real data points, going up to the year 2017 (BP, annual), are represented by black markers. The curves suggest that carbon contributions of oil and coal will continue to increase and reach a peak around 2040. Just a few years later, the summation of carbon from all sources reaches its maximum. There is a second peak, at a lower level, near the year 2110—that is the point where carbon production per year starts a definitive decline. Carbon from methane (natural gas) continues to rise until reaching a peak around the same time. The cumulative CO2 ppm in the atmosphere, reaching just over 800 ppm in the year 2150, is displayed on the right axis of the figure. Based on IPCC scenarios (2014), 800 ppm of CO2 corresponds to a temperature rise of approximately 4 °C.

Notwithstanding the fact that natural gas is cleaner burning than coal and oil, it is still a fossil fuel and therefore not by itself compatible with a low carbon future. In

[4] Carbon can be easily converted to CO2 emissions by multiplying the carbon value by 3.66 (the grams of CO2 associated with a gram of carbon—considering carbon has an atomic mass of approximately 12 units, while CO2 has about 44 units).

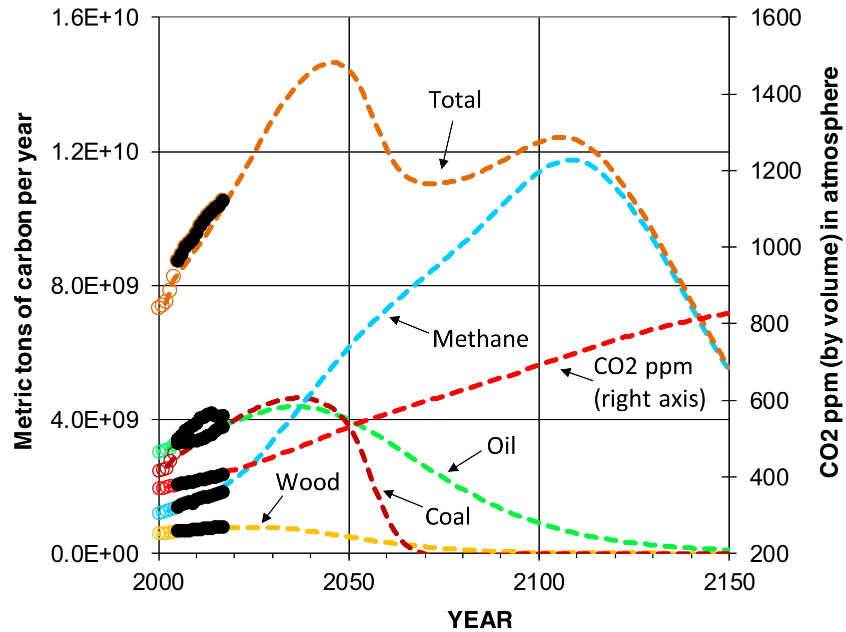

Fig. 5 Projected global carbon levels until 2150. The total reaches a peak around 2040–2050. Real data to 2017 (BP, annual) represented by black markers

the absence of renewable energy development over the long run, Fig. 6 shows that natural gas production would generate a substantial amount of carbon, which would surpass that of oil and coal around 2030. Thus, natural gas would have to act as a transition to non-fossil energy sources in order to suppress carbon levels to those seen in Fig. 5. Possible renewable sources that can contribute significantly to the long-run energy mix include wind, solar, and hydrogen. The latter is an energy carrier that can be generated from natural gas but eventually would have to be produced from non-fossil matter; e.g., water.

Discussion

A key result of the modeling effort in Aguilera and Aguilera (2012) was the launching of the "low and zero carbon initiative," where it was indicated that methane (natural gas) becomes the leading fossil fuel in the global energy market as of 2030. In the second half of the twenty-first century, the modeling shows there is significant potential for non-fossil sources, which will possess the highest market share (surpassing methane) around the year 2070. Like the COP21 Paris Agreement, the GEM outcomes would not limit CO2 concentrations in the atmosphere to less

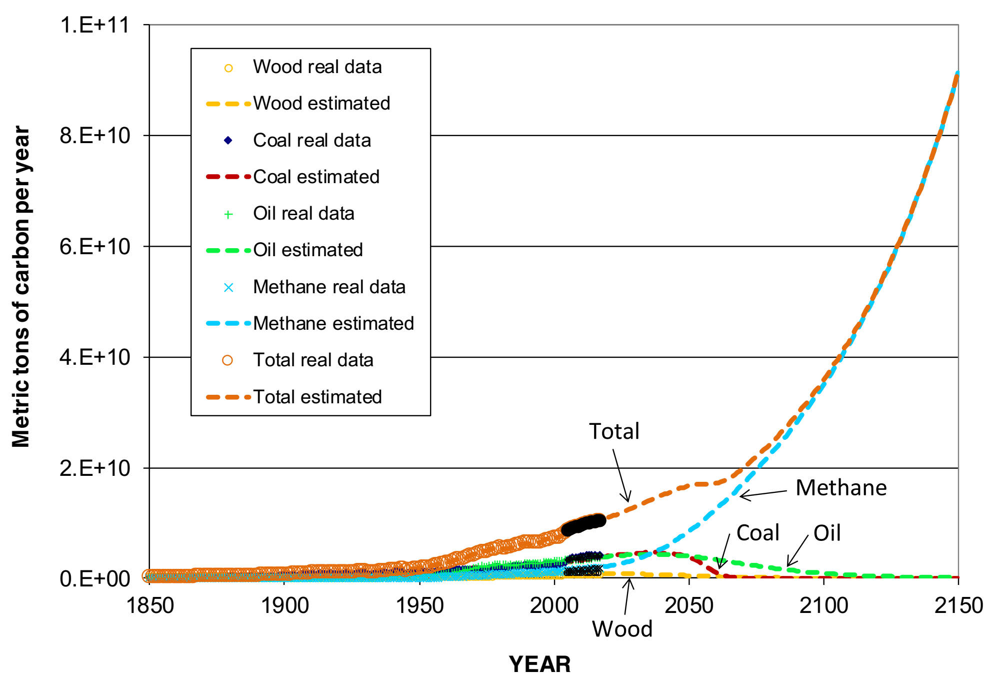

Fig. 6 Projected carbon levels if methane (natural gas) were to become the dominant fuel in 2150. Real data to 2017 (BP, annual) represented by black markers

than a doubling from pre-industrial levels. Future research may include alternative GEM scenarios, e.g., projections consistent with goals of the Paris Climate Agreement.

But it should be highlighted that our model is simply a simulation indicating what would happen if past dynamics were an indication of the future. In addition, it needs underlining that the uncertainties associated with global energy and environmental policies cloud the outlook for the energy mix, especially in the long run. For example, deep climate policies would have the potential to reduce energy consumption levels and alter the energy mix substantially. It is therefore essential to have increased understanding of the actions that encourage or discourage natural gas and renewable energy use.

Technological advancement will also play an important role in determining energy mix outcomes. Despite the innovation and cost reductions occurring in the renewable energy industries, and the theoretically massive energy potentials, significant technical and economic challenges remain. Intermittency is one of the major drawbacks—the most promising renewable sources such as solar and wind are not always available when required. Furthermore, there are still limited options for storage of electricity generated. Thus, rewewables cannot yet provide the scale of energy supply needed to displace fossil fuels. Continued technological advancement will be vital to create solutions for dealing with the intermittent generation of solar and wind power. This is where natural gas can play an important complementary role as a bridge fuel—power plants run on gas provide a backup for renewables when the wind or sun is unavailable. Eventually, demand-response management (e.g., in the form of smart grids) will have to be developed to shift flexible loads depending on the availability of the wind or sun. As technology progresses, storage of electrical power for later use to fill the shortfall could be a solution.

In order to transition to a low carbon future, it will be critical to exploit the vast natural gas endowments around the world. The GEM model implicitly assumes the enactment of favorable policies over the long run and continuous technological progress for the gas and liquefied natural gas (LNG) industries. The shale revolution has been a positive development in this regard. It is the result of technological progress—involving the application of horizontal drilling and hydraulic fracturing—that has made vast dormant gas resources economically exploitable (Aguilera and Radetzki 2014). Moreover, there have been substantial cost reductions in LNG production, transport and receiving technologies (Radetzki and Wårell 2017). However, further progress in the gas industry will not occur autonomously over time. Governments must create lasting incentives, and not disincentives, to produce conventional and unconventional gas resources and deliver them to the marketplace. This holds particularly true for a country like Canada as it looks to enter the highly competitive LNG industry. It is also relevant for Australia as it is poised to soon become the global leader in LNG—a position that may be difficult to maintain in the long run as lower cost competition from other countries enters the market.

Opportunities for substantial coal to gas substitution can be found primarily in Asia, since the region will account for the majority of the world's energy demand growth but is still heavily reliant on coal. Climate policies could play an important role here: a sufficient tax on carbon gives natural gas an advantage relative to coal, given the higher carbon intensity of the latter. This encourages technological improvements that further lower the relative price of gas and thus induce additional substitution from coal towards gas. It could also see natural gas capture oil's already declining market share in power generation and pave the way for gas to compete with oil in the transportation sector. Several countries around the world, including the US, Iran, Pakistan, and Argentina, are already using technologies like compressed and liquefied natural gas in their vehicle fleets.

Climate policies will also help to accelerate growth rates for renewables, albeit from a low base, and over time could make some renewables competitive with gas and coal. Nevertheless, further advancement in cost-reducing technology for renewable energy will be necessary to give it a competitive advantage in the long run.

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