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Should We Frack?

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This article examines the role of hydraulic fracturing (fracking) for natural gas production as a bridge fuel to a more sustainable future. The basic science, technology, risks, and benefits of fracking will be explored.

Christian Call to Care for Our Neighbors

As Christians we are called to seek the common good of our neighbors, both domestically and internationally. Pope Francis stated to the May 21, 2014, audience in Rome, "Creation is a gift, it is a wonderful gift that God has given us, so that we care for it and we use it for the benefit of all, always with great respect and gratitude." Care for our neighbors must take into account creation and our relationship to "the least of these" (Matthew 25:40). The common good is served by the development of safe, clean, and affordable energy sources for the enhancement of the quality of life for all, especially for "the least of these."

Realization of clean and affordable energy for all will require significant global financial investment over decades to develop and implement because the world has over one billion impoverished people. This situation also has an additional complication: namely, coal-fired electricity generation is dirty but inexpensive, while wind and solar are clean energy sources but expensive. Also, nuclear energy is moderately priced and clean, but the public is afraid of this technology. In the light of these complexities, what is the most loving way for Christians to advocate for clean and affordable energy for all?

The future global energy portfolio must address energy poverty and criteria pollutants (soot, smog, ozone, nitrogen and sulfur oxides, and toxic metals) in the short term and carbon emissions in the long term. Currently, technologies that address carbon pollution at a global scale (carbon capture and sequestration, wind and solar) are not economical. Therefore, since conserved energy is the cheapest and cleanest energy, conservation should play an immediate large role in the developed world. In the short term, to address the serious problem of criteria pollution, rapid global development of natural gas reserves by fracking (and, in the longer term, by nuclear power expansion) is necessary to replace the ~40% of global electricity generated from coal-fired facilities. This strategy acknowledges that coal-fired plants can be converted to gas-fired plants more rapidly than nuclear facilities can be constructed. In this manner, gas-fired power can serve as a bridge fuel for a few decades until a global gas/nuclear/wind/solar smart grid can be economically developed and deployed, and the public learns to trust nuclear energy.

Energy Conservation for the Rich and Energy Development for the Poor

The role of energy in global development and its importance for an adequate standard of living must be explored. The

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United Nations Development Programme has developed a semi-quantitative measure of overall material quality of life called the human development index (HDI). This index is composed of quantitative measures of "average national life quality" based upon three indicators: (1) life expectancy at birth, (2) per capita income, and (3) mean years of schooling. HDI values are reported every other year and range from 0 to 1 with a 2012 value (latest data) of 0.71 being the median value for the 187 ranked countries. Some examples of country values are (global HDI rank/HDI value) USA (#3/0.94), China (#101/0.70), South Africa (#121/0.63), India (#136/0.55), and Mozambique (#185/0.33).

An interesting presentation by David Larrabee at the 2014 ASA/CSCA/CiS Annual Meeting discussed the relationship between HDI and national per capita total energy consumption.[1] Some of this data is presented in table 1. He made three important points. First, above a per capita energy consumption of approximately 145 kWh/day, there is no correlation between HDI and energy use. For instance, Germany and Canada have similar HDI values yet very different per capita energy consumption. This suggests that ~145 kWh/day might be a good global target for how much energy the less-developed world will need for an adequate standard of living. Currently, the median per capita global total energy consumption is about 60 kWh/day. The 145 kWh/day value also sets a target for the developed world in terms of per capita energy conservation.

Secondly, below 145 kWh/day, there is a weak correlation with the HDI and energy consumption: generally, the lower the per capita energy consumption, the lower the HDI. Most interestingly, with very low per capita energy consumption (<20 kWh/day), there is a strong correlation: small increases in per capita energy consumption significantly increase HDI values. These data suggest that a program focused upon electrification of the most energy-impoverished regions will rapidly increase the global standard of living.

Table 1. National Human Development Index (HDI) versus Per Capita Total Energy Consumption. Data are for 2010 and from the presentation by David Larrabee at the 2014 ASA/CSCA/CiS Annual Meeting in Hamilton, ON.

Country	HDI	kWh/person/day
Norway	0.938	330
USA	0.902	254
Canada	0.888	310
Germany	0.880	145
Mexico	0.750	100
China	0.663	58
South Africa	0.600	40
India	0.519	15
Mozambique	0.284	5

The third interesting point was Larrabee's invitation to do a personal energy audit. This is the first step in addressing energy conservation in the developed world. The monthly electric bill is the best place to start since it measures a portion of our energy consumption. For example, my family's monthly electric bill allows convenient comparison of our electricity use to the values in table 1. Our highest electric bill typically reveals an average electricity consumption of 11 kWh/day/person that is about double the average per capita total energy use for Mozambique. However, comparing my family's daily electric usage with the per capita US total average energy consumption (11/254 x 100) accounts for only about 4% of total energy consumption.

According to the US Energy Information Agency (EIA), 40% of US energy consumption in 2011 was for electricity generation. This involves electricity used for residential, commercial, and industrial purposes. My household per capita daily electricity consumption represents only 10.2% of the US per capita daily electricity consumption of 102 kWh/day. Where is the rest of my family's per capita energy consumption?

Most electricity use in the US is for commercial and industrial purposes. Therefore, the largest portion of my "true" per capita electric "bill" (102 – 11 = 92 kWh/day) is for the electricity used to make items such as appliances, food, automobiles, tires, computers, cell phones, and other commodities of modern life. The American love affair with the automobile accounts for 27%, or 69 kWh/day, of the per capita US energy use. The missing 33% or about 84 kWh/day/person of US energy use must be accounted for by consuming products containing non-electrical energy from industries such as petrochemicals, refining, paper, construction, mining, pharmaceuticals, and heating. This analysis of my family's energy use reveals that a significant amount of our energy use was invisible to me. I was only aware of my transportation, home heating, and electrical energy consumption which accounts for only about one-half of the US per capita energy consumption.

This simple analysis of my family's per capita electric bill and its relationship to the average total per capita energy use illustrates two important points about US energy. First, not much electricity (and other energy) is required for the basic necessities of life: heat, cooling, lighting, clean cooking, refrigeration, food processing, clean water, and sanitation. Second, a typical US middle-class lifestyle could be reconfigured to use significantly less electricity without a significant decrease in lifestyle. Much electricity is used to convert natural resources into the materials used to construct buildings. Larrabee suggests that simply buying a slightly smaller house and delaying non-essential replacement of cars and electronic devices such as cell phones, computers, and TVs could save significant amounts of energy without significantly lowering our standard of living. Obviously, increased use of mass transit would also significantly decrease energy consumption.

At the other end of the energy spectrum are 1.2 billion people in the developing world without electricity, according to the World Bank. Most of these people live in India and sub-Saharan Africa. The previous discussion suggested that not much energy is needed to provide the basic necessities of life for the world's poorest. However, if providing this energy is linked to sustainable energy development, it will delay the poorest from obtaining these necessities. A review of World Bank energy projects over the last few years shows that only about 10% of the ~$9 billion spent annually on energy projects involved fossil fuels. At the current rate of World Bank-financed electricity development and estimated population growth, by 2030, there will still be over 1 billion people without electricity and 2.7 billion still without clean cooking capabilities. To address this issue by 2030 will require a significant increase in annual electrification expenditures.[2]

Table 2 presents estimates for the average US electricity costs for differing generation technologies. It is assumed that the facility will be generating electricity by 2019 and has a life cycle of thirty years. Although these estimates are for the US, it seems logical that the relative ranking for electricity costs for the differing technologies should be similar globally. However, global fossil-fuel prices will be a major variable that can change electricity prices and the commercial viability of the various technologies. For instance, only in the US is natural gas inexpensive; fracking increases the gas supply which makes gas-fired power plants economically viable. In addition, it has been suggested that the costs reported in table 2 for wind and solar have been significantly underestimated.[3]

To illustrate the complexity of green energy economics, we will examine a recent paper by Delucchi and Jacobson that addressed the feasibility of providing energy (electric power, transportation, and heating/cooling) with wind, water, and solar (WWS) power.[4] In this peer-reviewed paper, the authors examined the electric power needs of California over two years (2005 and 2006) to explore the feasibility of WWS power to meet minute-to-minute energy demand. To this energy-demand curve they then computationally deployed an imaginary electric grid with a capacity of wind (73.5 GW), water (26.4 GW hydroelectric), solar (26.4 GW of concentrated solar power and 28.2 GW of rooftop photovoltaic power), geothermal energy (4.8 GW), and a natural gas reserve (24.8 GW). The geothermal capacity is a base load (i.e., constant) energy source and was set at the maximum commercially available for California. It should be noted that geothermal energy production is commercially viable only in areas that are near tectonic plate boundaries; these result in the hot earth mantle being near the surface, as in California. Wind and sun are variable energy sources, whereas hydropower is a dispatchable energy source that can quickly adjust to meet fluctuating electric demand. In this study, the magnitude of hydropower available was limited

Table 2. Average US Levelized Cost Estimates (fuel and construction costs) for Electric Generation Rates in 2019. Subsidies have been excluded from cost estimates. Data from http://www.eia.gov/forecasts/aeo/electricity_generation.cfm.

Capacity Factor (%)	Technology	2012$/MWh
85	Conventional Coal	95.6
87	Gas-Fired Adv. Comb. Cycle	64.4
90	Advanced Nuclear	96.1
35	Wind	80.3
25	Solar Photovoltaic	130.0
20	Solar Thermal	243.1
53	Hydro	84.5
93	Geothermal	47.9

to the current amount allocated to California from the Pacific Northwest.

Based upon the weather records for 2005 and 2006, Delucchi and Jacobson were able to estimate daily, minute-by-minute, energy production curves for wind- and solar-energy sources. They were then able to dispatch hydropower appropriately in their model to balance grid-energy needs. It was found that 99.8% of the time, the model grid was able to meet the power demand of the WWS grid. However, over the course of two years, there were ~36 hours when the model needed electricity generation (~12 GW) from the natural-gas backup facilities. This amount of energy requires ~50 (500 MW each) gas-fired power plants on idle such that they can quickly power up to meet surging electricity demand.

This example of the hypothetical California WWS grid that needs ~50 natural gas power stations on standby to stabilize the grid against inevitable significant power fluctuations is very expensive. In essence, two power systems are needed to run simultaneously while being intricately balanced to keep the grid stable. In the real world, the ~50 natural gas power plants would need to be financed by a surcharge on the WWS electric bills.

Currently, countries that have significant amounts of solar/wind capacity in their grid, such as Germany at ~20%, are able to stabilize the grid inexpensively with their significant fossil-fuel capacity. However, incorporating greater than ~20% wind/solar capacity adds significant expense because of extra required dedicated dispatchable fossil-fuel capacity needed for standby unless special geographic conditions are readily available. Such is the case in Denmark which has ~20% wind capacity and is able to balance its grid by interfacing with the massive hydro-capacity in neighboring Norway and Sweden. When the wind is strong in Denmark, excess electricity is sent to the neighboring countries for immediate consumption while hydroelectric generation is decreased appropriately. When not enough wind energy is generated in Denmark, the neighbors increase hydroelectric production to dispatch to Denmark. This system is expensive and results in Denmark having the highest residential electric rates in Europe.[5]

There are many other significant issues with the Delucchi and Jacobson paper[6] and with green energy economics[7] that are beyond the scope of this article.

Addressing the other energy sources in table 2, commercial-scale geothermal and/or hydroelectric generation, where viable, has, by and large, already been deployed. Table 2 suggests that of the remaining commercial-scale technologies for electricity generation, gas-fired advanced combustion-cycle generators and nuclear are the most economical, and they are cleaner than coal technologies. Gas-fired power generation has an advantage over nuclear in that it can be deployed faster.

However, gas-fired power plants are only economically viable when natural gas is plentiful and consequently inexpensive. For instance, India is using only ~25% of available natural gas capacity because of a domestic shortage. A lack of infrastructure to import enough liquefied natural gas (LNG) to fuel all gas-fired generators has resulted in coal-fired power plants providing most of India's power.[8]

Coal is a dirty fuel. Globally, coal-fired power generates ambient particulate matter pollution that has been linked with 2.7 million premature deaths in 2012, according to the World Health Organization.[9] An additional 4.3 million deaths occurred due to indoor air pollution from cooking and heating. Of the ambient particulate matter deaths, 620,000 occurred in India while 1.2 million occurred in China. To address these deaths, China is implementing a plan to build facilities in rural western China that will convert coal into synthetic natural gas (SNG) to fuel new SNG-fired power stations in eastern urban areas. When fully implemented in ~2020, this will allow the closing of a significant number of urban coal-fired facilities, which will significantly improve urban air quality. This plan will also make it easier to capture the very significant amounts of CO_2 that are generated in the coal gasification/SNG generation process when carbon-capture and sequestration becomes economically viable.

It has been estimated that the carbon footprint of each of China's SNG power stations will be about seven times that of a similar natural gas-fired power station.[10] Rapidly developing China's shale gas potential would be much better than expanding the SNG process beyond 2020 in terms of both criteria pollution (soot, smog, ozone, nitrogen and sulfur oxides, and toxic metals) and carbon pollution perspectives. However, because of difficulties recently encountered in economically developing China's deep massive shale gas reserves, with 68%

more technologically recoverable gas than the US, it was announced that only half of the 2020 shale gas goal will be met. This new natural gas goal is set at 1.1 trillion cubic feet (tcf), while, for perspective, in 2012, the US produced 24 tcf. China has recently sought assistance from US companies in developing their shale gas potential.[11] In order to understand the problems that must be solved in developing China's shale gas reserves, horizontal drilling and hydraulic fracturing will be explored.

What is Fracking?

To properly answer this question, we must develop an understanding of conventional and unconventional drilling shown in figure 1. Conventional oil and gas development can be imagined with a vertical well, drilled thousands of feet below the surface to pierce geological formations that contain crude oil and/or natural gas. This is visualized in figure 1 by the left well, which is drilled into a conventional non-associated gas formation. A non-associated gas formation does not contain any oil while an associated gas formation contains both oil and gas. Conventional wells can tap formations that are *permeable*, that is, the residual hydrocarbons readily flow through the formation from high pressure to lower pressure at the wellhead. The well borehole contains concrete reinforced steel pipe to support the integrity of the well. The top portion of the well shaft is much thicker (not shown) due to additional layers of steel pipe and concrete designed to protect well water from contamination by the drilling process. Well water is typically less than one thousand feet below the surface while oil and gas deposits are typically deeper. The portion of the steel pipe in the hydrocarbon-rich geological formation must be punctured (perforated) to allow the hydrocarbons and brine to flow to the surface. Brine is concentrated salt water that is typically a natural component of hydrocarbon-containing geological formations.

Not all of the wells drilled in the world, as described above, are commercially viable. The cumulative expenses are significant: geological and drilling technology, labor, steel pipe, concrete, legal expenses,

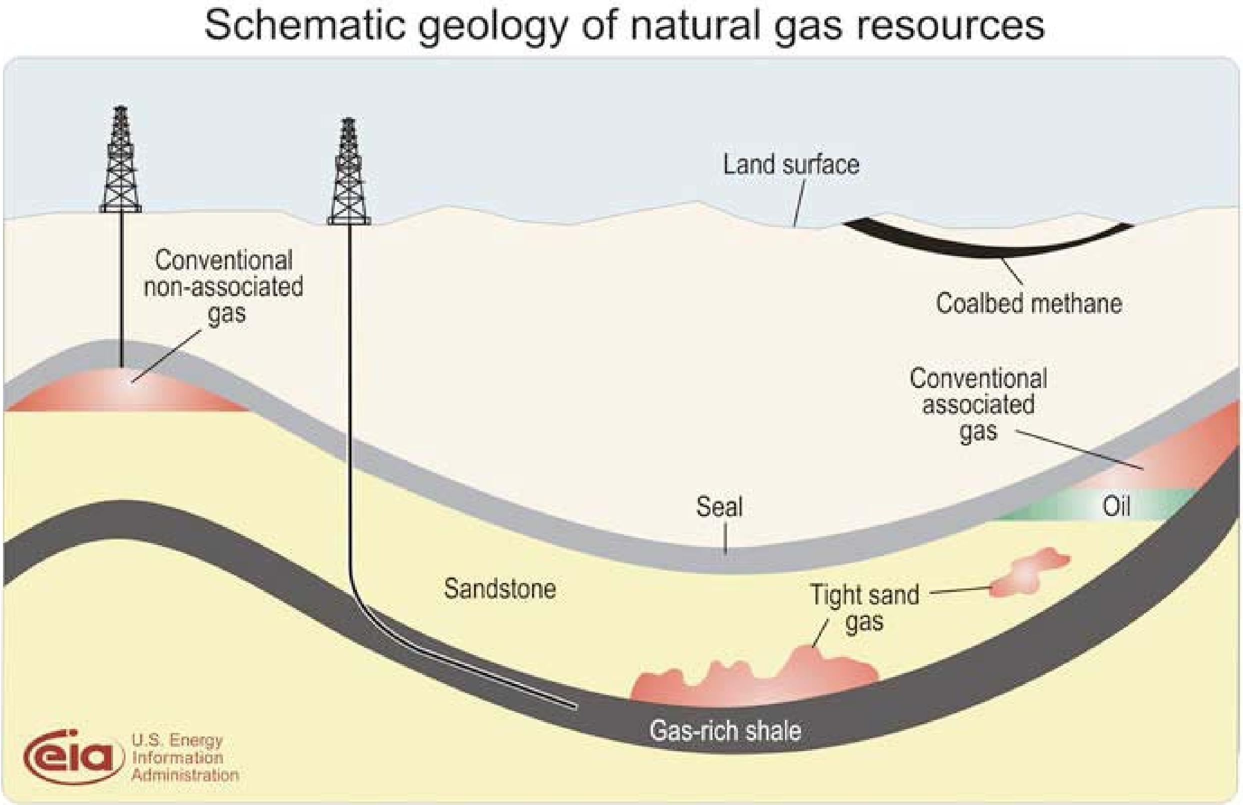

Figure 1. A generic depiction of conventional and unconventional gas wells.
Source: http://www.eia.gov/todayinenergy/detail.cfm?id=110.

landowner royalties, taxes, and establishing the infrastructure required to move oil and gas to market. The critical component necessary for commercial viability in the above well description is sufficient *permeability* in the geological formation to allow the oil and gas to flow at a rapid rate. However, vast amounts of hydrocarbon reserves are trapped in geological formations with poor permeability. To address the lack of permeability, Halliburton Company performed the first hydraulic fracturing in 1949.[12] The first high-volume fracturing was performed in 1968 by Pan American Petroleum. In 1965, a US Bureau of Mines publication wrote that

> Many fields are in existence today because of these fracturing techniques for, without them, many producing horizons would have been bypassed in the past 15 years as either barren or commercially nonproductive.[13]

Being unable to tap nonpermeable reserves would probably have caused a global energy crisis in the 1960s, which would have drastically slowed economic development. Recall that it was 1950 through the 1970s when the world made significant progress in feeding the growing population. Cheap oil contributed to this agriculture green revolution in food production. Fracking enabled abundant crude to flow from conventional wells, helping to keep nominal global prices low (<$40/barrel) through 2002 except during the geopolitical events in the 1970s.

Going back to the previous description of gas production in the vertical wellbore in figure 1, the details of hydraulic fracturing involve (1) injecting high-pressure water through the perforated steel pipe of the wellbore to induce fractures in geological formations, (2) forcing these fractures open to significantly increase the surface area of the formation in contact with the wellbore, and (3) inserting into these induced fractures a proppant, such as sand, to hold the fracture open after the hydraulic pressure is relaxed.

The mixtures used to fracture wells are typically composed, by volume, of ~90% water, ~9% proppant, and ~1% chemicals. The role of the water is to facilitate fracturing and expanding the geological formation surface area; the proppant inserts into the fractures to maintain their integrity after the pressure is released. The roles of the chemicals are many. First, the viscosity of the water is increased in order to keep the proppant sufficiently dispersed to allow the proppant to become embedded in the fractures with the water. Second, when the fracture process is complete, "breakers" are introduced to decrease the viscosity of the fracturing fluid. The fracturing fluid along with brine, referred to as flowback water, readily flows to the surface (owing to the viscosity decrease) as the hydrocarbons are released from the formation. Third, an assorted array of services provide lubricity, corrosion inhibition, plus antiscalant and antibacterial functions.

The tremendous pace of research and development in the oil-field chemicals industry has resulted in decreasing toxicity of fracturing chemicals, with a simultaneous increase in performance. For instance, Halliburton has developed CleanStim, a fracturing fluid formulation that employs chemicals used in the food industry. In a recent public relations stunt, twenty drilling executives sipped on CleanStim (without the antibacterial) to emphasize its lack of toxicity.[14]

It has only been since 2004 that the oil and gas industry has had the technology to perform directional drilling on a commercial scale. George Mitchell is credited with developing horizontal (i.e., unconventional) drilling combined with hydraulic fracturing to start the commercial development of the Barnett Shale in Texas.[15] Unconventional drilling is depicted in the right-hand wellbore in figure 1. Unconventional wells typically go down at least one mile before drilling one or more miles horizontally. Hydraulic fracturing of the geological formation is required to stimulate enough hydrocarbon production to make drilling such massive wells economically viable.

A great example of the potential role of unconventional gas in promoting cleaner energy is found in current developments in the Indian natural gas market.[16] It was previously mentioned that India was using their natural gas power at only 25% capacity because of a shortage of domestic natural gas. The Indian government just started coupling the price of domestic natural gas with international markets. In the short term, this move has doubled Indian gas prices; in the long term, this move will allow industry to develop India's shale gas reserves with unconventional drilling which will produce domestic natural gas much cheaper than imported LNG, which is currently priced at over $12 per million BTU. In the long term, this move will significantly improve India's air quality.

Developing China's unconventional resources has many technology problems and economic issues that must be addressed. First, China's gas reserves tend to be found at levels deeper than those in the US, which tend to be less than 10,000 feet. Fracking in deep deposits needs advanced proppant technology that can survive high pressures and temperatures. This technology has been developed in the US and involves the use of ceramic proppants that are coated with special polymers.[17]

Second, China has a freshwater shortage that will limit the capacity to frack deep wells with millions of gallons of freshwater. Fortunately, fracking in the dry regions of the US has forced the development of technology that uses minimal freshwater or no water at all. Fracking with minimal freshwater involves reusing ~20% of the produced water, water that returns to the surface after fracking, and blending it with brine. This mixture is then used to frack the next well.[18] In Texas, brine is obtained by drilling brine wells on-site. Also, special additive chemistry was developed to allow the gelling agents, surfacants, and antifriction, antiscalant, and antibacterial additives to function properly in saltwater.[19] In regions where brine is unavailable, fracking can be done by using nitrogen, CO_2, or propane instead of water. However, this technology is more expensive and also more dangerous.

Fracking has a good safety record, but, as with any human enterprise, accidents do happen. For instance, in June 2014, an explosion and fire occurred during a Halliburton fracking operation in Ohio.[20] The explosion was caused by a bursting hydraulic hose which sprayed oil unto a hot engine causing the initial fire. Fortunately, no serious injuries were reported, but an estimated 70,000 fish were killed when fracking chemicals and produced water flowed into a tributary of Opossum Creek to the Ohio River. If this site had been fracking with propane rather than water, most certainly many deaths and injuries would have occurred.

Deep gas wells fracked with brine water containing polymer-coated ceramic proppants will be an expensive operation, requiring high gas prices to make the operation economically viable. According to the US Energy Information Administration (EIA), imported LNG in China was priced at over $14 per million BTU's in October 2014. This high price is an incentive for launching an extensive shale gas-drilling program to increase domestic Chinese natural gas. Such a program could significantly decrease Chinese natural gas prices. Use of the latest technology developed in US gas fields could result in the Chinese gas wells being more productive than US wells. The trick is to find the "sweet spot" in the shale deposits prior to drilling and fracking, which can result in a ten-fold increase in gas production. The state of the art in oil- and gas-prospecting technology uses 3D microseismic imaging to look for the geological fingerprints of sweet spots. This technology exploits the capacity of seismic waves to become distorted in low-density environments such as microcavities that contain oil and gas. Currently, Chinese drilling companies are planning to work with prospecting companies such as Halliburton and Schlumberger, both pioneers in "sweet spot" technology.[21] Finally, the economics of Chinese gas wells should look better in the future as US companies are currently developing "cross-unit drilling" techniques that are significantly lowering well costs.[22] Collaboration between Chinese and major global energy companies has great potential to increase domestic natural gas production with concomitant coal displacement in power generation resulting in reduced future criteria and carbon emissions in China.

Environmentally Responsible Fracking?

In 2011,*The Future of Natural Gas* was published. This report is an in-depth interdisciplinary MIT panel report chaired by Ernest Moniz, the current Secretary of Energy. This report states,

> With over 20,000 shale wells drilled in the last 10 years, the environmental record of shale gas development has for the most part been a good one. Nevertheless, it is important to recognize the inherent risks of the oil and gas business and the damage that can be caused by just one poor operation; the industry must continuously strive to mitigate risk and address public concerns.[23]

Table 3 presents data from major gas drilling incidents that were widely known based upon media coverage between 2005 and 2009. About half of the incidents that occurred were damaging to ground (well) water, natural gas intrusions because of deficient well casings.

In 2012, the Royal Society and the Royal Academy of Engineering published a peer-reviewed analysis of fracking. The review examined the risks of unconventional drilling from the perspective of water management issues, well integrity, fracking-induced seismicity, and natural-occurring radioactive materials. The review states,

> The health, safety and environmental risks associated with "fracking" … can be managed effectively in the UK as long as operational best practices are implemented and enforced through regulation. Hydraulic fracturing is an established technology that has been used in the oil and gas industries for many decades.[24]

Consistent with this view is a 2014 peer-reviewed article by Susan Brantley and colleagues detailing a thorough analysis of Pennsylvania records on shale gas development water issues from 2008 through 2012.[25] During this period, more than 6,000 wells were drilled and more than 4,000 were completed (i.e., fractured). Brantley et al. estimate that approximately twenty gas wells unambiguously contaminated well water while thirty large spills also occurred. Most of the well-water contamination incidents occurred in the eastern part of the state and involved faulty well casings that permitted methane migration into water wells. This occurred in 0.24% of the gas wells developed. The most famous incident occurred in 2009 in Dimock, PA, where a faulty well casing resulted in increased methane levels in residential wells in eighteen homes.[26] Because of these water well contaminations, the industry has improved the safety protocols required (i.e., enhanced well casings) when drilling permeates drinking water formations to prevent possible water contaminations.

Table 3. Major Widely Known Gas-Drilling Incidents between 2005 and 2009. Source: Table 2.3 in Moniz et al., "The Future of Natural Gas: An Interdisciplinary MIT Study."

Type of Incident	Number Reported	Fraction of 43 Total Incidents
Groundwater contamination by natural gas or drilling fluid	20	47%
On-site surface spills	14	33%
Off-site disposal issues	4	9%
Water withdrawal issues	2	4%
Air Quality	1	2%
Blowouts	2	4%

The Dimock incident stimulated research efforts that culminated in three significant recent publications. A peer-reviewed publication by Duke University researchers suggested that methane found in some sampled wells had isotopic carbon 13 and deuterium signatures consistent with thermogenic methane as opposed to biogenic (microbial) methane.[27] This result suggests the possibility of methane migration from the very deep Marcellus shale entering shallow water wells. A more recent study examining over 1,700 predrilling water samples suggests that the thermogenic methane detected in the Duke study was not derived from the Marcellus shale but from shallow hydrocarbon-containing geological strata that are in direct contact with certain water wells.[28] The most recent report was from the US Geological Survey which suggests that some water wells in parts of eastern Pennsylvania, in regions with no gas drilling activity, contain thermogenic methane from geological strata above the Marcellus shale along with elevated concentrations of some brine components (strontium, barium, arsenic, bromide, chloride, sodium).[29] All of this work illustrates the importance of predrilling drinking water sampling and that additional research is required.

Recent concerns have been raised over fugitive methane emissions since the greenhouse gas (GHG) potential of methane is significantly higher than that of CO_2. Larry Cathles and colleagues, in a peer-reviewed argument, suggest that this fear is unfounded, since fugitive methane emissions are less than 3% of natural gas production from well to customer.[30] In addition, Cathles has also provided very interesting modeling data that suggest a possible role for natural gas in improving our future global carbon footprint.[31] Three different scenarios for future fossil-fuel consumption profiles were examined. These scenarios all assume that between 2005 and 2105 the global energy system will grow to provide for the estimated future ~10 billion inhabitants, each with a European level of energy consumption (7 kW per capita or ~74 terrawatts globally/yr or ~168 kWh/day per capita).

The first scenario, "business as usual," increases global energy consumption 2.1% per year until 2055, utilizing primarily a mix of fossil fuels. The global energy growth rate increases only 1.2% per year over the next fifty years with declining fossil-fuel use and increasing use of noncarbon energy sources. The second scenario assumes flat petroleum consumption and rapid displacement of coal by natural gas in electricity generation for the first fifty years. In the second fifty years, both gas and petroleum are rapidly replaced by noncarbon energy sources. The third scenario involves the first fifty years with gas and petroleum consumption constant and coal being rapidly replaced by noncarbon energy. In the second fifty years, gas replaces petroleum. The global carbon footprints of these three scenarios over one hundred years were calculated to be 1268, 935, and 544 gigatons carbon (GtC), respectively. Since the Industrial Revolution, global anthropogenic carbon emissions are estimated to be about 600 GtC.

It is believed that limiting cumulative anthropogenic carbon emissions to one trillion tons is necessary to keep future average global temperature increases about 2 °C above pre-industrial temperatures.[32] Only in Cathles's third scenario is the carbon budget in line with a ~2 °C temperature increase. We previously saw in the analysis by Delucchi and Jacobson that massive deployment of noncarbon energy at this time is not economically feasible.[33] Cathles's second scenario is more economically feasible, in that there is time to optimize the noncarbon energy systems; however, the higher carbon budget for this scenario increases future average global temperature by ~3 °C. It is estimated that the "business as usual" scenario will drive global temperatures to ~4 °C above pre-industrial temperatures.

It can be argued that the US has inadvertently set out on Cathles's second scenario. According to the US EIA, shale-gas displacement of coal-fired electricity generation has already resulted in a 10% decrease in US GHG emissions between 2005 and 2012. For comparison, GHG reductions in the EU were 14%, while Germany observed 4% in the same time frame.[34] In September 2014, the US EPA released the fourth annual GHG emissions report, which found 2013 methane emissions from the petroleum and natural gas industry down 13.3% from 2008.[35] This is in spite of a 400% expansion in drilling and fracking activity since 2008. The largest component of this decrease has been a 73% reduction in emissions from fracking.

However, tracking GHG emissions is more complicated than the above-cited EIA data suggest. To illustrate this, table 4 presents a comparison of select national CO_2 emissions with data for total GHG emissions when imports and exports are considered. Table 4 succinctly summarizes what has happened globally in the last ten years with respect to carbon pollution on a per capita basis. The selected five countries represent the world in 2001; the first three European countries represent developed countries that were the first to address carbon pollution. For instance, Norway has had a carbon tax since 1991 while Germany and Denmark are currently global leaders in alternative energy deployment. In 2001, these countries had CO_2 emissions about half that of the US. China represents the less-developed world, which is currently committed to economic development, and in 2001 only emitted about one-third of the per capita CO_2 of the European countries. In the

Table 4. Select National CO_2 Emissions in 2001; Total National Greenhouse Gas (GHG) Emissions in 2001, including Imports and Exports; and Select National CO_2 Emissions in 2010.

Country	National fossil fuel CO_2 emissions in 2001[a] (metric tons per capita)	Total national GHG emissions including imports and exports in 2001[b] (metric tons per capita)	National fossil fuel CO_2 emissions in 2010[a] (metric tons per capita)
Denmark	9.2	15.2	8.3
Germany	10.4	15.1	9.1
Norway	9.1	14.9	11.7
United States	19.7	28.6	17.6
China	2.7	3.1	6.2

[a]Per capita CO_2 emission data is from the World Bank and is only from fossil fuel development, consumption, and cement manufacturing.
[b]This data is from Hertwich and Peters, "Carbon Footprint of Nations: A Global, Trade Linked Analysis," and includes estimates of total per capita national greenhouse gas (GHG) emissions (CO_2, CH_4, N_2O, fluorinated gases) at the point of consumption, including those from imports and exports.

middle column are estimates for these countries with respect to total climate emissions.[36] These estimates include emissions from GHG's and address CO_2 at the point of consumption in terms of global trade. The significant per capita increases were observed in climate emissions for the top four.

Clearly, in 2001 Chinese imports were not "exporting" western climate emissions. However, this picture changed somewhat by 2007 with 22% of China's carbon footprint attributable to exports.[37] A similar trend is observed in the 2010 CO_2 emissions data for Norway, which increased 28% from 2001. Since 97% of Norway's electricity is hydroelectric, the bulk of this CO_2 emissions increase is from oil and gas production and manufacturing. Norway's main exports are hydrocarbon fuels, refined metals, chemicals, machinery, ships, and fish.[38] Production of five out of six of these products requires significant CO_2 emissions.

Although the data in table 3 and the discussed studies suggest that the environmental record of the oil and gas industry is relatively good, it must continually improve to gain the popular support required for further development. In 2013, the Center for Sustainable Shale Development (CSSD) in Pittsburgh, PA, was started to promote enhanced environmental standards. The goal of this organization is to work with all stakeholders (industry, government, and the environmental community) to help industry working in the Marcellus Basin increase standards for field engineering and environmental control activities by adapting transparent, objective, continuous improvement processes. These best practices involve the entire range of gas operations. CSSD will use these standards to facilitate third-party inspections to verify that those audited are meeting these best standards. These standards are generally more rigorous than those required by state environmental agencies. In April 2014, Chevron was the first company to be certified. For instance, the standards for groundwater protection include the following:

1. Zero discharge of waste water until adoption of treatment standards
2. Greater than 90% waste-water recycling
3. Closed loop containment of drilling fluids to minimize water use during drilling
4. Double-lined water impoundments with leak detection
5. Groundwater monitoring both pre- and post-operation
6. Casing and cement standards
7. Disclosure of well stimulation fluids
8. Spill response and public notification plans

The standards for air pollution include the following:

1. Removal of hydrocarbons from flowback and produced water before storage
2. Reduced emission completions
3. Emissions standards for drilling rigs, frack pump engines, compressor engines, trucks
4. Condensate tank emissions control

The key to successful shale development involves increasing stakeholder trust by developing and adopting objective continuous improvement processes.

Can Global Unconventional Energy Development Promote "Cleaner" Human Development?

The development of unconventional (horizontal) drilling and hydraulic fracturing has revolutionized the global energy landscape in just ten years. This technology has enabled the economic development of deep, thin, geological formations containing oil and gas. It has significantly increased oil and gas reserves in the US and transformed the global energy landscape in amazing ways. Ten years ago, the prospect of global peak crude-oil production was a serious economic issue facing the US economy, the world's largest consumer of crude. However, application of unconventional drilling techniques to shale-oil formations in North Dakota and Texas has led the International Energy Agency (IEA) to predict that the US will soon be the world's largest producer of crude oil, surpassing both Russia and Saudi Arabia. In addition, British Petroleum projects that by 2030 the world will use 30% less petroleum than in 2011 because of enhanced fuel efficiency standards and increased use of renewable energy and natural gas. Rapid global displacement of coal by natural gas in power generation also has the potential to improve urban air quality and further limit carbon emissions.

The transformation of the US energy landscape by unconventional drilling and fracking can be expanded internationally to provide natural gas as a bridge fuel. However, this must be done carefully and prudently to minimize the extent of wanton economic development. Global development ideally should be coupled with a version of the Roman

Catholic Church's vision of human development. Wolfgang Grassl points out that from such a vision each human is called to a vocation "to be more" in terms of emotional, spiritual, educational, health, and economic spheres.[39] This is referred to as *authentic human development* to distinguish it from mere economic development, which if left unchecked by healthy spirituality, becomes destructive.

William Oddie explains this in a different manner in an interesting essay on *Laudato Si'* (Praise Be to You) as follows:

> So how are the poor to cease to be poor? Only as a result of their economic development. As Charles Moore asked on Saturday: "Why is the developed world rich? The answer lies in the name: it developed more than other places. Development happens by uniting the resources of the earth with the capacities of the human brain and the institutions of human society. The resulting innovations are driven by energy, the cheaper the better. Hence the overwhelming historic (and present) importance of fossil fuels."[40]

From this perspective, it is useful to reflect upon Pope Benedict XVI's encyclical *Caritas in Veritate* (Charity in Truth), which focuses on the problems of global development and progress toward the common good. The Pope writes,

> Charity in truth, to which Jesus Christ bore witness by his earthly life and especially by his death and resurrection, is the principal driving force behind the authentic development of every person and of all humanity. Love—*caritas*—is an extraordinary force which leads people to opt for courageous and generous engagement in the field of justice and peace. (p. 1)

Benedict points out that the "Truth" of humanity's transcendent vocation to progress "drives us to do more, know more, and have more in order to be more" (p. 16).

Benedict also reminds us that

> Technology, viewed in itself, is ambivalent. If on the one hand, some today would be inclined to entrust the entire process of development to technology, on the other hand we are witnessing an upsurge of ideologies that deny *in toto* the very value of development, viewing it as radically anti-human and merely a source of degradation. This leads to a rejection, not only of the distorted and unjust way in which progress is sometimes directed, but also of scientific discoveries themselves, which, if well used, could serve as an opportunity of growth for all. The idea of a world without development indicates a lack of trust in man and in God. It is therefore a serious mistake to undervalue human capacity to exercise control over the deviations of development or to overlook the fact that man is constitutionally oriented towards "being more." (p. 14)

I pray God will be with us as we help, in our own small ways, to bring God's mercy, justice, prosperity, and peace to all. ✦

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