Fugitive Methane: The Promise and Pitfalls of the Shale Gas Revolution

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Abstract

The combination of hydraulic fracturing and directional drilling has prompted a boom in natural gas production from previously inaccessible shale formations, resulting in shale gas representing a share of production equal to that of conventional gas. U.S. demand for the fuel is projected to increase with overall energy demand and with retirement of coal capacity in the industrial and electricity generation sectors. The Shale Gas Revolution, as this boom in production is called, has prompted investment and stimulated economic activity in the regions that contain these shale resources and has placed the U.S. on a path toward energy self-sufficiency. Shale gas development brings its own environmental issues, namely potential groundwater contamination and direct emission of methane into the atmosphere. There is also the larger issue of declaring natural gas as the solution to energy issues when climate science dictates that a carbon-minimal, renewable energy-powered future is the best way to avoid the worst impacts of climate change.

The literature discusses the sources of fugitive methane emissions and its impact on the evaluation of the potential of shale gas from a climate change standpoint. Considering methane a stronger greenhouse gas, Howarth et al. estimate several points of methane leakage that make shale gas' greenhouse gas footprint larger than coal. Measurements taken from production sites find a much lower methane emissions rate, and its results are corroborated by the harmonized estimates of eight studies. Allen proposes envisioning climate change using cumulative emissions, which removes the weighting of certain gases in favor of a 1 trillion tonne carbon emissions budget for the entire industrial and post-industrial periods. While the literature disagrees on the amount and the importance of fugitive methane, it agrees that technology and infrastructure play a large role in minimizing fugitive emissions and avoiding a future negatively impacted by climate change.

Introduction

Hydraulic fracturing, used in conjunction with horizontal drilling, has revolutionized the energy landscape of the United States. As with any revolution, it has its proponents and opponents — the former point to the potential U.S. energy independence and to its promise as a low-carbon alternative to coal; the latter express concerns about the environmental impact of increased fossil-fuel use and methane leakage. Environmental concerns about increased natural gas production surround the pollution of groundwater by drilling and production, and (as the global warming effect of methane is being studied and updated) fugitive emissions of methane directly to the atmosphere. This paper will first discuss modern day practice of hydraulic fracturing (usually called "fracking"), summarizing the phases of production from well creation to delivery at end-use sites. Further sections following will summarize the domestic and international economic effects of the recent boom in U.S. production of natural gas and the myriad environmental issues and concerns. The issue receiving the most attention will be fugitive methane emissions, with a discussion of the sources, potential solutions, and effects of this phenomenon. Many of the topics discussed in this paper are being studied intensively and our understanding is continuously informed by new information. This paper will try to highlight the evolution of this understanding during the past few years.

Section 1: The Process of Hydraulic Fracturing

Shale gas, along with tight gas and coalbed methane, is considered an unconventional fossil-fuel resource. While the exact meaning of unconventional is subject to changing economic and technological realities, the first two resources are commonly found in shale "plays", a geographic area containing organic-rich, fine-grained sedimentary rock. In order to be considered a viable unconventional play, this rock must have the following characteristics:

1) Clay to silt size particles
2) A high percentage of silica and/or carbonates
3) Thermally mature
4) Hydrocarbon-filled pores
5) Distribution over a large area
6) Low permeability (<1 millidarcy (Wang et al. 2014)) that can be effectively increased by fracture stimulation to reach economic production levels (Caputo 2011)

The combination of technology advancements in hydraulic fracturing and directional drilling has dramatically increased the accessibility and production of natural gas, particularly in the United

States. This boom in production and the growth of supporting industries is commonly known as the Shale gas evolution, named for the main type of gas that has become increasingly accessible.

The boom in natural gas production has come about through a combination of two technologies. The first is high-volume, slick-water hydraulic fracturing – the process of creating fractures in shale to allow methane gas trapped in its pores to flow into a well. Hydraulic fracturing has been used to enhance the productivity of permeable conventional oil and gas reservoirs since the 1940 (Montgomery and Smith 2010), but the high-volume techniques characteristic of its use today in unconventional reservoirs – impermeable shale formations – have been used extensively only in the last ten years (Howarth, Ingraffea, and Engelder 2011) to access previously unrecoverable stores of natural gas. Directional drilling allows a well to penetrate and follow an individual layer of shale for long distances – many kilometers – maximizing the exposure of the well to the shale layer, enabling effective exploitation of shale layers that are thin but widespread. The fracking process opens, in the shale layer, artificial fractures that tap into natural fractures to provide channels through which the methane in the rock's pore space can flow toward the wellbore and up to the surface.

To produce unconventional shale reservoirs, a well is first drilled directly downward into the Earth to reach a shale layer that is usually several kilometers deep. For example, the Marcellus Shale in northern Pennsylvania can occur at depths from 0.6 to 3 kilometers beneath the surface.[1] After the drill clears the near-surface freshwater zone, the drill string is removed and steel well casing is inserted in order to separate the wellbore from the surrounding earth (to ensure that the well does not collapse) and to isolate it from groundwater (so as to not contaminate the surrounding water). The well is cemented in place with a thin layer of cement that is injected into the annulus between the outer wall of the casing and the rock formation. After the shallow zone is cased, the drill string is reinserted to continue drilling. Frequently, the section of the well that intersects the near-surface freshwater is double-cased and double-cemented to minimize the chance that produced gas will leak into the surrounding drinking water.

[1] Marcellus Center for Outreach and Research. Pennsylvania State University.

As the well approaches the target shale, the drill begins to turn horizontally, forming a gentle curve that enters the shale layer at a near horizontal angle. The drill can continue to bore horizontally for several kilometers, after which the drill is removed from the well and the entire length of the well is cased and cemented. After cementing, the casing is perforated along the lateral (the horizontal section of the well) using shaped charges conveyed on a device called a perforating gun. Fracking fluid, primarily composed of water and sand, is pumped into the well at high pressures; the pressurized water enters the shale formation through the perforations in the casing and opens artificial fractures that connect with natural fractures in the shale. The network of connected fractures is held open by the sand and other particles in the fluid called “proppants”. This phase if the operation (perforation and fracking) is usually conducted in stages on different sections of a given lateral, each about 100 to 200 meters in length. The methane in the pore space of the shale layer is able to flow into these propped open fractures and back up the well, expelling the fracking fluid, and entraining in the reverse flow some of the natural pore water in the rock, and its dissolved minerals. This combination of water and fracking fluid, called flow-back water, contains sand, chemicals, dissolved gas and minerals and must be kept in chemical tanks or surface ponds. A single region of a shale layer may be penetrated by several wells drilled from the same wellpad, which allows for a relatively small surface footprint relatively to the area of the underlying shale that is being drained. A typical pattern has six wells extending in opposite directions from the well pad and space several hundred meters apart.

While this technique is most famously used to exact natural gas from shale, fracking is applicable in essentially any “tight” formation – those that are characterized by rocks of very low permeability. The process of fracking shale can also produce oil from liquid-rich shale formations and be used as secondary recovery methods in existing oil and gas wells. An important example has been the production of tight oil, particularly in the Eagle Ford Formation (Texas), the Permian Region in southern Texas, and in the Williston Basin in North Dakota and Canada. The advent of this source of oil has pushed the amount of imported oil processed at Gulf Coast refineries to historical lows[2] and has significantly boosted U.S. production in recent years, reversing a long-term

[2] This Week in Petroleum: Crude Oil Imports Continue to Decline

decline in U.S. oil production that started in the 1970s. The U.S. produces about ~4 million barrels of crude oil produced each day from tight oil formations (Aloulou 2015).

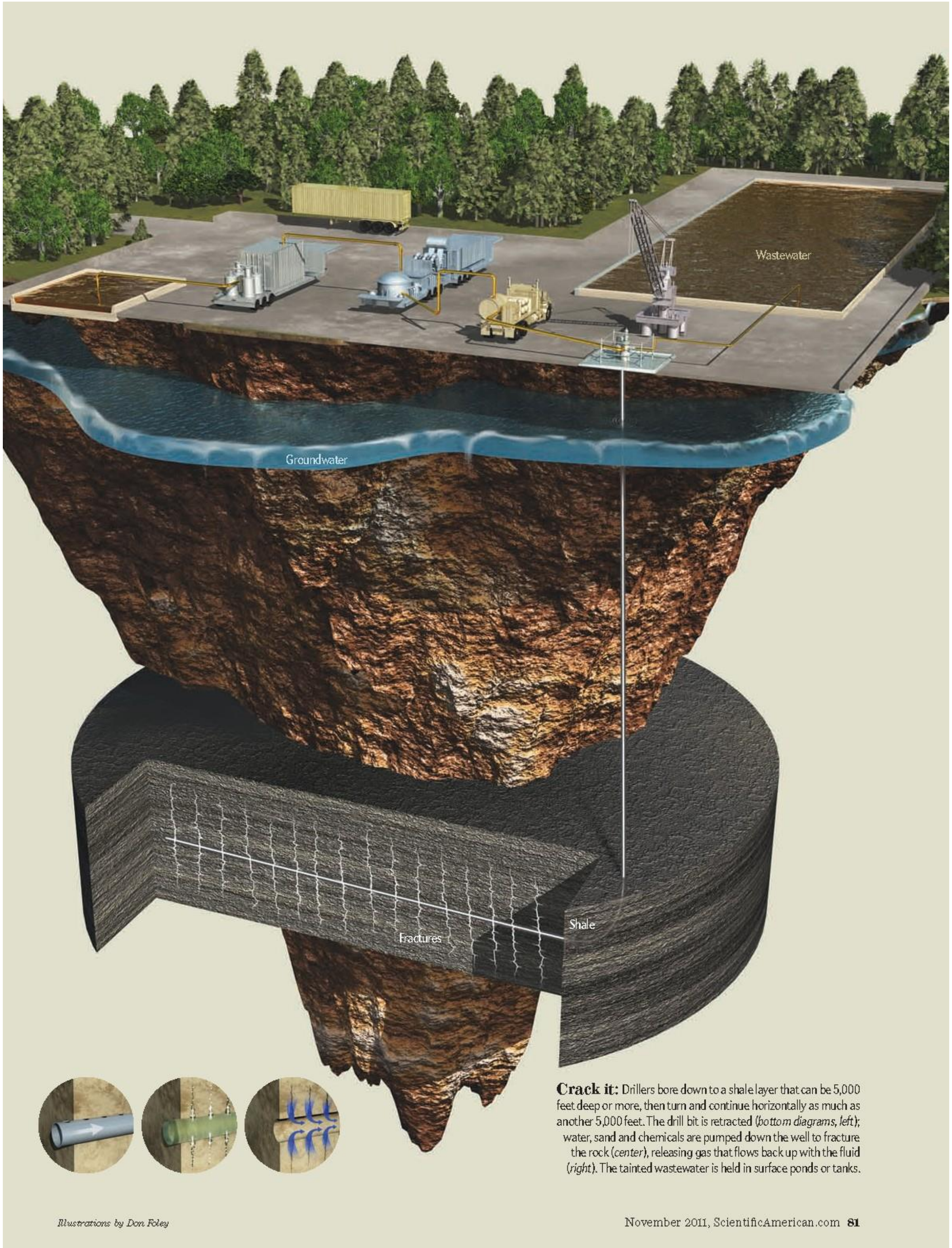

Figure 1. Diagram of a pad with a single vertical and lateral. Scientific American

Section 2: The Economic Effects of Fracking in the United States

Natural gas is the fastest growing fossil fuel relative to oil and coal, with an annual growth rate of 1.9% per year[3] (BP 2015). The advent and continued growth of fracking techniques and shale gas production have had a large effect on U.S. energy production, which increased by 3.2% in 2013 – surpassing the production growth levels of all other countries and reaching an all-time high in domestic production for the fourth consecutive year. The U.S. also realized similarly impressive growth in oil production, growing by 1.1 million barrels/day to reach a total of 10 million barrels/day, the highest level since 1986 (BP 2014). Most of this growth can be attributed to fracking: shale gas constituted about 30% in 2013 of U.S. natural gas production (up from 4% in 2007 and is expected to contribute 50% by 2040), natural gas accounted for 33% of US domestic energy production in 2013 – third consecutive year with natural gas as the dominant produced energy source in the U.S. This, combined with the fact that coal's share of energy consumption remains steady at around 18% in the face of growing energy consumption, reflects the ascent of natural gas as a primary fuel for electricity generation. The EIA's 2015 Annual Energy Outlook projects that natural gas share of consumption will increase to nearly 29% by 2040, led by increases in the electric power generation and industrial sectors and accompanied by the retirement of 40 gigawatts of coal-fired power plants. The United States produced 84% of its domestic demand natural gas, an all-time high that puts it well on the path to energy independence. The BP Energy Outlook 2035 estimates that the United States will be energy self-sufficient (energy independent) by the year 2021, exporting up 9% of its energy supply by the year 2035.

The shale-gas revolution has dramatically changed the face of United States fossil fuel production, considerably increasing the size of gas reserves via previously inaccessible (economically speaking) gas-bearing shale formations. An example is the Marcellus Shale, a shale formation dating to the Devonian that was not considered a major gas resource before 2007 due to the inaccessibility of the contained gas. The shale itself covers most of the Appalachian Basin, extending southward

[3] Compared to 0.8 % for both oil and coal

from southern New York and enveloping the northwestern half of Pennsylvania, the eastern half of Ohio, and the majority of West Virginia.

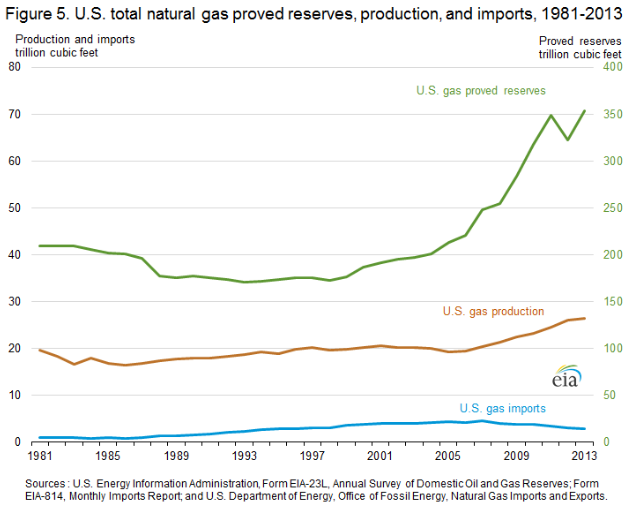

Figure 2. Fossil Fuel Production, Reserves, and Imports. U.S. EIA

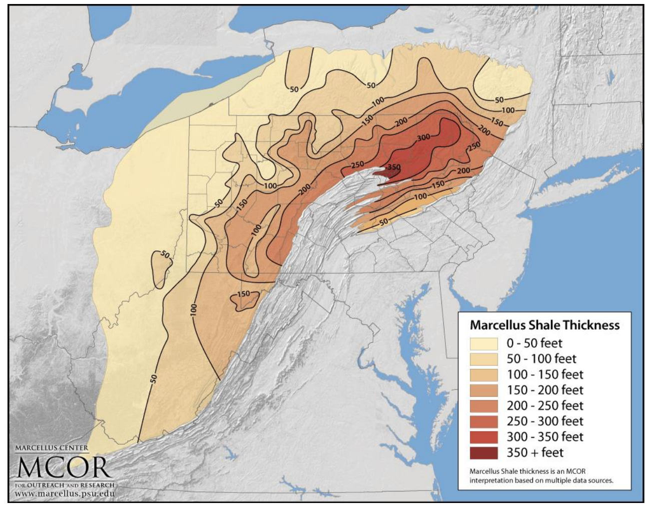

Figure 3. Geographical Extent of the Marcellus Shale. MCOR.

Fracking and horizontal drilling have made the Marcellus shale the largest domestic source of natural gas with proved reserves of 64.9 trillion cubic feet, according to the latest EIA figures, and with estimates up to 187 trillion cubic feet of technically recoverable gas (US EIA 2014). The growth of Marcellus shale production is particularly notable due to its proximity to the major cities (and the accompanying energy demand) of the East coast (Durham 2008). In the reference case of the EIA's 2014 Annual Energy Outlook (as simulated by NEMS, the National Energy Modeling System), Marcellus shale production exceeds 100% of the projected natural gas demand of the Northeast and Mid-Atlantic census regions from the year 2016 to 2040. As a result, the 2014 AEO projects that Marcellus shale gas will be transported to other domestic markets and (contingent on transportation technology) international markets as well.

While the Marcellus shale is by far the largest source of shale gas, there are five other major shale plays that combine with the Marcellus to provide the lion's share of shale gas production: Barnett (Texas – 26 tcf of reserves), Eagle Ford (Texas – 17.4 tcf of reserves), Haynesville (Texas/Louisiana – 16.1 tcf of reserves), Woodford (Texas/Oklahoma – 12.5 tcf of reserves), and Fayetteville (Arkansas – 12.2 tcf of reserves). These six plays combine with 10 tcf from other shale gas sources to give 159.1 tcf of natural gas – slightly less than 166 tcf of reserves in conventional wells of the continental U.S., but still accounting for 45% of the country's proved reserves.

Natural gas is not the only fossil resource that has seen increased availability as a result of the increased use of fracking. Tight oil has been a particularly valuable resource, because oil still represents the largest source of primary energy in the U.S. accounting for 35% of primary energy used in 2014; 71% of this oil used was used by the transportation sector, where it constitutes over 90% of the energy used in transportation in the U.S. Similarly to shale gas, the bulk of tight oil production is concentrated in two plays, with four other plays providing relevant amounts of tight oil. The two highest producing plays are the Bakken (North/South Dakota, Montana – 4.8 billion barrels reserves) and the Eagle Ford (Texas – 4.2 billion barrels of reserves), which together account for 90% of tight oil reserves. The Bone Spring (New Mexico/Texas – 335 million barrels of reserves), Marcellus (Pennsylvania/West Virginia – 129 million barrels of reserves), Barnett (Texas – 58 million barrels of reserves), and the Niobara (Colorado/Kansas/Nebraska/Wyoming – 17 million barrels of reserves) are the other major sources of tight oil. While shale gas has become a major

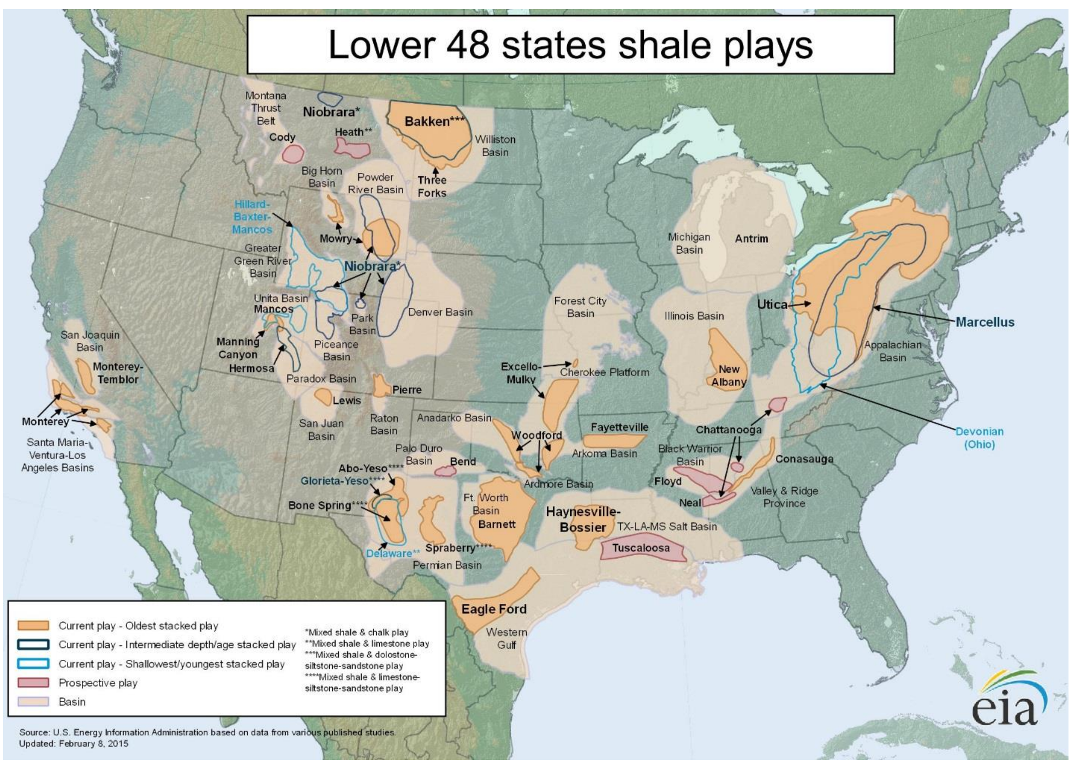

Figure 4. Lower 48 States Shale Plays. U.S. EIA.

portion of US natural gas, tight oil accounted for a smaller fraction. 27% of produced oil in 2013 (US EIA).

As with any growing industry, shale-gas production has created jobs in technical and supportive roles. However, there is some debate over the size of the effect; at the core of the debate are questions about exactly which jobs can be attributed to the fracking boom in states such as Pennsylvania, Texas, and Louisiana, which have seen the largest increases in shale-gas production. What is undeniable, however, is that the new accessibility of these fossil resources has given the oil and gas industry a boost that has been reflected in employment figures. From the beginning of 2007 to the end of 2012, the oil and gas industry increased its employment by 162,000 jobs, or 40% -- impressive in comparison to the 1% gained by the private sector as a whole. However, the oil and gas sector only comprises 0.5% (roughly 570,000 of almost 150 million jobs in 2012) of private sector employment in its core job categories. The Bureau of Labor Statistics (BLS) classifies the oil and gas industry under the mining sector, and divides jobs within the natural gas industry into three categories: Drilling, Extraction, and Support. Drilling[4] has shown the smallest job growth both absolute and in percentage terms, increasing by 6600 jobs to account for 90,000 jobs at the end of 2012 -- an 8% increase over that time period. Extraction[5] has exhibited larger growth, increasing by 53,000 (a 38% increase) jobs to account for 193,000 at the end of 2012 and exceeding a January 2012 BLS projection of 180,000 extraction jobs by the year 2020 (Henderson 2012). The largest category within the oil and gas industry (accounting for half of all employment in the industry) is Support, which over the same five-year period grew by 102,000 jobs to employ 286,000 individuals – a 55% increase. The BLS defines support as "involving performing supporting activities for oil and natural gas operations, including exploration, excavation, well surveying, casing work, and well construction – BLS considers support to be for the above activities, and does not include jobs created in other industries such as manufacturing, housing, retail, education, and food services". While BLS does not directly attribute contemporaneous growth in other sectors to the fracking boom, economic

[4] BLS defines drilling as "involves any employment related to the spudding and drilling of wells, as well as reworking of wells."

[5] Extraction includes establishments primarily engaged in operating, developing, and producing oil and natural gas fields, including exploration and all production work up to the point of shipment from the producing property.

benefits of the shale gas revolution often include ancillary job creation and the benefits of the inexpensive fuel that accrued to consumers.[6]

Pennsylvania is an interesting example, as it has seen a sharp uptick in fracking activity in the Marcellus shale. Since 2007 (the start of the financial crises that led to the Great Recession), jobs in mining and logging (which include fracking jobs) have risen by nearly 17,000, an 80% increase.[7] However, in a February 2014 op-ed Pennsylvania Governor Tom Corbett claimed that "More than 240,000 Pennsylvanians work in our oil and gas industries and in jobs made more secure by its existence" (Corbett 2014). Pennsylvania labor statistics classify Marcellus-related employment into two categories. The first category is Core industries, which are six industries that conform to the idea of traditional oil and gas jobs: crude petroleum and natural gas extraction, oil and gas well drilling, pipeline construction and maintenance, pipeline transportation of natural gas, and natural gas liquid extraction. The second category is termed "Ancillary Industries" and includes 30 industries whose jobs they believe are owed to the Marcellus shale: these industries include fossil fuel power generation, highway, street, and bridge construction, environmental consulting, real estate leasing, and general freight and trucking. Core Industries accounted for 33,157 jobs in Q3 2014, while the ancillary industries yielded 216,299 jobs in the same time period – combining these figures explains the 240,000 jobs claimed by Governor Corbett.[8]

While it is difficult to overstate the effect of the Marcellus shale on the Pennsylvania economy, Governor Corbett may have done so. An important concept in certain branches of economics is the multiplier – that money spent by governments and/or individuals, when the wider economic effects are considered, has an impact larger than the face value of the initial expenditure. The inclusion of 30 ancillary industries as Marcellus-driven claims that each job in one of the core industries is responsible for nearly 7 jobs outside of it – a strong claim that does not appear to be

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[6] Today in Energy: Oil and Gas Industry Employment Growing Much Faster than Total Private Sector Employment. August 8 2013. http://www.eia.gov/todayinenergy/detail.cfm?id=12451.

[7] Pennsylvania Fast Facts, March 2015. Pennsylvania Department of Labor and Industry Center for Workforce Information and Analysis.

[8] Marcellus Shale Fast Facts, 1st Quarter 2015 Edition. Pennsylvania Department of Labor & Industry, Center for Workforce Information & Analysis.

supported by enough data.[9] It is also difficult to determine whether in ancillary industries would support a similar number of jobs in the absence of the Marcellus, and to what degree ancillary employment would decrease with a decrease in core industry employment. These issues may be difficult to predict, but extended periods of low natural gas prices may offer an opportunity for observation if there is a contraction of the core industries. While the economic effects are crucial to the U.S. goal of energy independence, less than 10,000 of the 216,299 ancillary jobs are environmental consulting or conservation administration. While the environmental effects of fracking are still being explored, the diversity and seriousness of potential issues appear to merit more than 4.22% of jobs attributed to the Marcellus shale.

Section 3: The Environmental Effects of Fracking in the United States

An ancillary industry cited as benefiting from the Marcellus shale is the electric power generation industry. Natural gas is heralded as a positive development for a carbon-constrained future due to its potential to replace coal as an energy source. In 2014, 17.9 quadrillion BTU (British Thermal Units; a BTU is about 1 kilojoule, kJ, of energy in S.I. units) consumed in the United States are estimated to have coal as its source -- 18% of the US total energy use for that year.[10] 91% of that coal goes to the electric power generation (the electric power sector generates 32% of US fossil fuel emissions), where it is the largest source used at 42% (US EPA 2015). The electric power sector generates 32% of US fossil fuel emissions. As coal is the largest contributor to the largest energy use source, its inefficiencies and unnecessary emissions are primary targets for optimization and lowering of greenhouse gas emissions. Natural gas is already a larger source of energy consumption in the industrial and residential/commercial sectors (it has proven to be a versatile fuel, used for electricity generation, cooking, and residential heating and cooling), so reductions in electricity produced from coal filed power plants are simultaneously beneficial to the environment and bringing the electric power sector in line with the others.

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[9] Admittedly, it is difficult to measure the impact of natural gas boom in Pennsylvania.

[10] Primary Energy Consumption by Source and Sector, 2014. EIA Monthly Energy Review, March 2015. http://www.eia.gov/totalenergy/data/monthly/pdf/flow/css_2014_energy.pdf

Coal is a heavy CO_2 emitter for two reasons: its energy density and its combustion pathway. The only chemical product of coal combustion is CO_2[11], while methane releases both CO_2 and water[12]. Additionally, coal is a very dense fuel, with an energy content of about 30 MJ/tonne of bituminous coal. As a result, bituminous coal emits 88.25 kilograms of CO_2 per gigajoule of energy derived from combustion – roughly 60% greater than the 50.34 kilograms of CO_2 per gigajoule of energy derived from natural gas (Hong and Slatick 1994). If the U.S. were to exchange all of its electricity-bound coal in 2014 for natural gas[13], it would save about 650 million metric tonnes of CO_2 emissions in a single year.[14] In addition to CO_2, coal is known for potentially emitting sulfur dioxide, nitrous oxide, and mercury when used as fuel. Power plants are also the "largest remaining source of several toxic air pollutants…including arsenic and cyanide" (US EPA 2011). Further, combustion of coal results in the production of particulate matter and ash which are known to cause adverse health reactions in children and contain trace amounts of radioactive substances (Hvistendahl 2007). The lack of these combustion byproducts is a major mark in favor natural gas, making it friendlier to the environment and health of individuals.

While the benefits of replacing coal with natural gas are numerous, the drawbacks of natural gas production and use are worth considering. Fracking has an environmental impact that is debated but potentially injurious, and widespread use of natural gas will still emit carbon dioxide and contribute to climate change.

The carbon-reduction benefit of a natural-gas dominated fossil fuel landscape may be mitigated by increased demand and production. Three major factors may increase natural gas demand over the coming years. The daily spot price[15] for one million BTU worth of natural gas is \$2.59 – a low price that both the natural gas industry, the renewable energy industry, and environmentalists would like to see increase. A higher price increases profits for the natural gas industry and allows for the price-

[11] $C+O_2 \rightarrow CO_2$
[12] $CH4+2O2 \rightarrow CO_2+2H_2O$
[13] This number is to illustrate the difference in CO_2 emitted by coal vs natural gas, and does not take into consideration other factors such as gas-fired power plant capacity or economic viability.
[14] Calculated by multiplying the per-gigajoule difference in my emissions by the amount of electricity consumption provided by coal
[15] As of April 21, 2015

competitiveness of solar and wind renewable energy. Further, an increase in gas price would be reflected in the final cost of energy from gas-fired plants, providing a financial incentive to consume less. While the United States has undergone gradual decarbonization (mostly due to technology advancements), there is concern that the low oil and gas prices may contribute to a rebound effect. This can be best understood using the example of cars and gasoline: expensive gasoline (caused by expensive oil) has caused changes in transportation habits such as increased pedestrian traffic and public transportation use, both of which have decreased carbon from the transportation sector. A rebound effect would occur if the newly low gasoline prices persisted and caused an increase in individual automobile use, erasing the gains previously made (Gillingham, Rapson, and Wagner 2015).

The sub-$3 price of natural gas is in large part due to the increase in reserves and production of natural gas – in no small part due to the shale gas revolution. While it is impossible to say for certain, increases in demand may provide enough upward pressure on gas prices to effect the changes listed in the previous paragraph. Demand fluctuates based many factors (temperature has a large effect on residential and commercial use), but the prospects of natural gas breaking oil's dominance over the transportation sector and the potential for energy self-sufficiency and export appear to be two potential sources of long-term demand increase. The transportation sector obtained 92% of its energy from petroleum, nearly 25 quadrillion BTUs – the remaining 8% of its energy came from natural gas (3%) and renewable energy (5%)[16]. Further penetration of natural gas into the transportation sector (via natural gas vehicles or gas-to-liquid conversion technologies – public buses have demonstrated this, as some run on natural gas) will provide consistent demand for natural gas. However, the viability of natural gas to an automotive fuel may be limited by its energy density – gasoline has a higher energy density by volume than liquefied natural gas.[17] Another source of sustained demand, as the BP 2035 Energy Outlook suggests, will be the international demand for natural gas once the US is energy independent and exporting in the 2020s. While this is heavily

[16] Primary Energy Consumption by Source and Sector, 2014. EIA Monthly Energy Review, March 2015. http://www.eia.gov/totalenergy/data/monthly/pdf/flow/css_2014_energy.pdf
[17] SOURCE THE WHOLE PARAGRAPH

dependent on transportation technology, Russia provided nearly 40% of the European Union's natural gas imports on 2007 and the EU may be prepared for a competing supplier of gas.

One of the major environmental concerns surrounding increased production of natural gas by fracking[18] is the role of water. Water is a major concern for two reasons: fracking uses large amounts of water in a time of growing overall water demand, and fracking uses toxic chemicals that may find their way from fracking fluid into drinking water. While the exact composition of fracking fluid is proprietary in many circumstances, roughly 98-99% of fracking fluid is water (King 2012) – the final percent is comprised of sand and other chemicals. A 2011 report released by the US House Committee on Energy and Commerce detailed some of the chemicals used in fracking fluids[19] by the fourteen leading oil and gas service companies and found that these companies "used 2.9 million m^3 of hydraulic fracturing products in their fluids from 2005-2009…this does not include the water that the companies added to the fluids at the well site before injection" (Waxman, Markey, and DeGette 2011). Assuming these products comprise the non-water portion of fracking fluid, estimated water usage (given that number) tops out at 295 million m^3 of water in those five years. A 2011 report from the US Environmental Protection Agency (EPA) gives a much higher estimate at 530 million m^3 of water used annually (Jägerskog et al. 2014). While this figure pales in comparison to the 277 billion m^3 and 176 billion m^3 of water used by the thermoelectric generation and agricultural sectors in 2005, through the explosive growth of fracking may lead future conflicts over water resources.

The large amount of water used in fracking is not the only concern surrounding water, as there are also concerns about the leeching of methane and fracking fluid into surrounding groundwater. Methane contamination is a concern due to the risk of explosion[20] and the fact that groundwater in communities near fracking sites may be the only source of water for drinking and agriculture. A paper by (Osborn et al. 2011) found that:

[18] All energy generation processes are water intensive, and fracking is no exception.
[19] The chemical content released was from fluid used from the years 2005-2009.
[20] There are multiple anecdotes and online videos of people lighting their tap water on fire, suggesting methane contamination.

> Methane concentrations were detected generally in [85%] of drinking water wells…but concentrations were substantially higher closer to natural gas wells. Methane concentrations were 17-times higher on average in shallow wells from active drilling and extraction areas than in wells from non-active areas. The average methane concentration in shallow groundwater in active drilling areas fell within the defined action level for hazard mitigation recommended by the US Office of the Interior. (Osborn et al. 2011)

The authors were also able to determine using isotope ratios that the methane in groundwater near active shale-gas production sites was of thermogenic origin (as opposed to biogenic), associated within produced methane. When comparing the groundwater in active and non-active areas, the non-active sites had lower concentrations of methane contamination and an isotopic signature consistent with mixed sources of gas – both bio- and thermogenic. Near the active areas, they observed a much higher concentration of methane that was nearly exclusive thermogenic. Because the study was based on a small number of wells (fewer than 100), many authors have contested the conclusion of the authors that the observed methane is due to natural-gas production. A more recent study involving thousands of wells in the Marcellus showed little correlation between thermogenic methane and proximity to shale-gas production sites (Siegel et al. 2015). The possibility of groundwater contamination by methane released during shale-gas production is still an area of active research.

A more pressing concern is that the use fracking fluid or flowback water can leak into the groundwater, since both can contain toxic chemicals. While there is less evidence for flow-back contamination than there is for methane contamination, there are three key ways by which it could get into groundwater: Open-air pits or ponds that are used to store flow-back can overflow or leak into the surrounding area; well casings could wear thin and crack; and new fractures could connect with older fractures from abandoned or retired wells. The latter pathway is particularly concerning due to the routine practices of fracking a single shale layer multiple times.

A relatively recent potential side effect of fracking practices is earthquakes. Areas in North Texas and Oklahoma have seen an unprecedented increase in earthquakes since fracking activities began in the area.[21] In 2013, Oklahoma recorded 109 earthquakes of magnitude 3 or more on the Richter scale, an amount inconsistent with the seismology of that region of North America. In 2014, the number of magnitude 3+ earthquakes increased to 585, far surpassing 2013's total and prompting intense scrutiny of potential causes. While fracking relies on high-pressure injection of fluid to produce hydrocarbons, the earthquakes are not considered a direct result of fracking operations. A more likely culprit has been identified in disposal of flow-back in deep injection wells. It was observed that epicenters for a series of earthquakes in 2008 and 2009 were all within 3 kilometers of a wastewater injection well, leading some to believe that injection rate and volume may assist in predicting the seismic potential of a given area (Ellsworth 2013). In response to the earthquakes and literature the Oklahoma Secretary of Energy and Environment announced the creation of the Coordinating Council on Seismic Activity to "work cooperatively to develop solutions, identify gaps in resources and coordinate efforts among state agencies, researchers and the state's oil and gas industry".[22] While the state has recognized the potentially causal relationship between disposal wells and earthquakes, it is unclear what action the state will take to reduce the earthquake risk in the areas surrounding disposal wells. Rodriguez and Soeder (2015) observe that over 95% of wastewater from oil and gas extraction sites across the country is injected into disposal wells, with exact figures varying based on geography, regulation, and availability of disposal wells. Injection is the most common disposal method in Texas and Oklahoma[23], while 72% of Marcellus wastewater is recycled (71% of drilling fluids, 90% of flowback water, and 56% of produced water). Recycling water could alleviate the earthquake problem and reduce the water demand for fracking operations – though the effectiveness relies on the amount of water recovered relative to the amount injected.

Natural gas is heralded as a large step in the transition toward a low-carbon or carbon-free society. As mentioned earlier, the displacement of coal in favor of natural gas will lead to a 43% decrease in carbon emissions per unit of energy generated by gas instead of coal. In a scenario where

[21] Anecdote: While I was in Irving, Texas for 2014-15 winter break, I experienced roughly a dozen earthquakes in the three-and-a-half weeks I was there.
[22] Earthquakes.ok.gov
[23] 0% of wastewater is recycled in the Permian Far West region.

there is no additional demand for natural gas past that required to replace coal, replacement of coal will reduce the total amount of carbon dioxide emitted and the rate at which it is emitted. However, in the more likely scenario that the demand for natural gas increases (particularly as transportation technology increases the economic viability of exporting natural gas), the overall amount of carbon dioxide emissions will increase (albeit more slowly than it would if coal were the primary energy source). (Allen et al. 2009) argue that the comparative emissions advantage of natural gas over coal will only be realized if natural gas is actually used as a transition fuel – not as a destination fuel that is merely "better than coal". This is because climate change is sensitive to cumulative carbon emissions rather than the rate of emissions. If the use of shale gas eventually means, over the long run, that more CO_2 is emitted into the atmosphere than would have been emitted if the Shale Gas Revolution had not occurred, then shale gas is not a net win in combatting climate change. This argument will be explained further in the next section.

While carbon dioxide is the centerpiece of most conversations about climate change and greenhouse gas emissions, methane is also a powerful greenhouse gas when released into the atmosphere. A major concern associated with the increase in natural gas production is the possibility of methane leaking from production infrastructure directly into the environment – known as fugitive methane. While it is possible to trivialize fugitive methane as an inefficiency endemic to the production process, its impact is great enough to warrant closer examination.

Section 4: Fugitive Methane

Fugitive methane is the name given to direct emissions of methane from fossil fuel production sites. The EPA estimates that natural gas production and distribution is the second largest source of anthropogenic methane emissions, contributing an amount of methane equivalent to 159.9 million metric tonnes of CO_2 in 2013[24]. Within natural gas systems, the EPA estimates that field production accounts for 31% of methane emissions and 42% of non-combustion CO_2 in

[24] 1 ton CH_4 = 22.7 metric tonnes CO_2e or 25 tons CO_2e. http://www.epa.gov/gasstar/tools/calculations.html

2013.[25] However, a 2013 paper by Scot M. Miller contends that the EPA estimates and EDGAR[26] inventories underestimate the contribution of gas production to anthropogenic methane emissions. Direct methane emissions are critically important because the strength of methane as a greenhouse gas is important when examining the greenhouse gas footprint of the shale gas production sites.

Methane and carbon dioxide are called "greenhouse gases" because they induce Earth's greenhouse effect – they absorb and re-radiate thermal radiation that warms the atmosphere. There exists a natural greenhouse effect (not unique to Earth[27]), without which the Earth would be significantly colder. But this effect is now being amplified by anthropogenic emissions of greenhouse gases. Carbon dioxide causes the most problems due to its ubiquity as a fossil fuel emissions and the fact that it remains in the atmosphere for thousands of years.

While CO_2 is well established as the greenhouse gas that will contribute extensively to future warming, it is not the "strongest" greenhouse gas. In addition to methane and CO_2, water vapor, ozone, and nitrous oxide are other greenhouse gases present in the atmosphere in non-trivial amounts. As a measure of the "strength" of a greenhouse gas (the potential of a gas to contribute to global warming), the Intergovernmental Panel on Climate Change has used Global Warming Potential (GWP). GWP, as initially defined in 1990 in a paper by Lashof, is a way of quantifying the relative contribution of a greenhouse gas to global warming. His original formulation compares the radiative forcing of a given gas in the atmosphere to the forcing caused by CO_2 and is given by:

$$GWP_i = \frac{\int_0^\infty a_i(t)c_i(t)dt}{\int_0^\infty a_c(t)c_c(t)\,dt}$$

GWP_i is the global warming potential of gas *I* while " a_i is the instantaneous radiative forcing due to a unit increase in the concentration of gas *i*, and c_i is the fraction of gas *i* remaining at a given time, and a_c and c_c are the corresponding quantities for CO_2." (Lahsof). The IPCC now defines GWP as

[25] US Environmental Protection Agency (2015) *Draft of Inventory of U.S. Greenhouse Gas Emissions and Sinks:1990-2013*

[26] Emissions Database for Global Atmospheric Research (EDGAR)

[27] Venus displays a stronger greenhouse effect than Earth as its atmosphere is 96% CO_2

"the time-integrated radiative forcing due to a pulse emission of a given gas, over some time period (or horizon) relative to a pulse emission of carbon dioxide" (Shine).

The IPCC provides GWPs for greenhouse gases on 20-year, 100-year, and 500-year time periods. The values for methane are 72, 25, and 7.6, respectively. Thus, depending on the time period, methane has a warming potential that is anywhere from 7.6 to 72 times that of CO_2 (IPCC 2007). The significant decrease in GWP over longer periods of time is due to the fact that methane reacts with hydroxyl radicals in the troposphere and stratosphere to form carbon dioxide (similar to the combustion of methane), pushing the GWP of methane toward that of CO_2 as it decomposes. GWP is far from a perfect metric, however, as there are factors that (if accounted for) can increase the GWP of methane. If the ability of methane to inhibit the formations of sulfate aerosols[28] (which have a cooling effect) is considered, the 20-year GWP rises to 105 and the 100-year GWP rises to 33 (Schrag 2012). Further, the atmospheric decomposition process is moderated by methane concentration – the more methane is directly emitted into the atmosphere, the slower the decomposition rate and the higher the GWP.

Schrag argues that GWP is a flawed metric because it considers the radiative forcing of a gas instead of the "global average temperature response to a pulse emission in a climate model". An alternative, Global Temperature Potential (GTP), quantifies the temperature response to a greenhouse gas emission given the existing concentrations of other gases as opposed to the radiative effect of the emitted gas itself. This approach, while dependent on the climate model used, universally yields lower GTP values for gases with a short residence time (such as methane). The 100-year GTP for methane is 7, three times lower than the corresponding GWP and lower than the 500-year GWP for methane.

Considering the life cycle of a natural gas production site, its greenhouse gas footprint is a function of three factors: direct CO_2 emissions (from final consumption of the fuel), indirect CO_2 emissions (from fossils fuels used to produce the gas), and direct methane emissions. Sufficient direct emissions from natural gas production sites (both conventional and shale gas) would increase the

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[28] Sulfate aerosols are partially a byproduct of coal combustion. If coal is phased out then it would stand to reason that sulfate emissions would decrease as a result, unless geo-engineering efforts were undertaken.

greenhouse gas footprint of these sites and diminish natural gas' advantage over coal. To identify the effect of fugitive methane on the greenhouse gas footprint of shale gas production sites, (Howarth, Santoro, and Ingraffea 2011) estimate fugitive methane as a fraction of overall production by examining potential losses in each stage of the production process for conventional and shale gas. This paper identifies five stages at which losses are most likely to occur: Well completion, routine venting (and associated equipment leaking), liquid unloading, gas processing, and transportation, storage, and distribution.

Well completion, the first stage at which losses can occur, is "the process of preparing a newly drilled well for production" (Heath et al. 2014). Well completion is the stage at which fracking occurs in shale gas production, and accounts for the major difference in the fugitive methane proportions when compared to conventional gas wells. Fracking that occurs later in the life of the well is termed "recompletion" and can yield further production and emissions. The flow-back period, during which fracking fluid is expelled from the well just after fracking, is characterized by large quantities of dissolved and gaseous methane in both shale and tight-sand gas formations. Howarth compiled data from two shale and three tight-sand formations and found that flow-back emissions correlated strongly with flow-back period length and initial gas production after well completion. Methane emissions as a percentage of life-time production ranged from 0.6 to 3.2%, so Howarth used the mean (1.6%) to represent well completion emissions. Drill-out, another stage in developing shale gas resources, is another methane-emitting process that Howarth conservatively estimates to release 0.33% of lifetime gas production. Combined (and excluding recompletion), Howarth estimates emissions of 1.9% of lifetime production for shale gas during the well completion phase, in comparison to .01% for conventional gas.

Another stage at which nontrivial leakage occurs is during venting. Well infrastructure is designed to occasionally vent gas in order to avoid excessive pressure buildup in the system, and (Howarth, Santoro, and Ingraffea 2011) identify pneumatic pumps and dehydrators to account for the majority of the leakage during this stage. In keeping with the previous stage, the paper uses a conservative estimate of 0.3% leakage to represent the use of best available technology. In some wells, leakage may occur during "liquid unloading" – a process that removes water from conventional wells as internal well pressure decreases. This process may result in a maximum of 0.26% leakage, although few shale gas wells require this unloading. Another scenario-dependent measure that results in leakage is gas processing, which may be necessary to remove other hydrocarbons and impurities from the gas before it is transported via pipeline. The need to process varies by geography, even within a single shale. The paper observes that Northeastern Marcellus shale gas is generally "pipeline ready", while gas from the Southeastern portion off the same shale requires processing. Different studies have yielded emissions rates of 0.19% (facility emission factor) to 0.76% (processing plan measurements).

The last stage with potential for fugitive emissions is also surrounded by the most uncertainty – transport, storage, and distribution. Studies have provided estimates for leakage rates that range from 0.53 to 2.5%, but are subject to limitations in the data. Using "lost and unaccounted for gas" yields estimates of 2.5 to 10% worldwide, although this figure encapsulates political turmoil (the fall of the Soviet Union and gas theft) in addition to poorly maintained infrastructure – neither of which applies to the environment in which the Shale Gas revolution is occurring. Another interesting development is the adverse reaction of the natural gas industry to leakage regulation. Texas proposed a 5% cap on fugitive methane in order to limit lost and unaccounted for gas, which was 2.3% in 2000 and had grown to 4.9% in 2007. While it is entirely possible, that industry opposed the regulation on principle, the growth of fugitive methane combined with the industry response to the legislation make the 5 % cap seem like an increasingly reasonable estimate for leakage in certain scenarios.

Combining these emissions estimates yields an estimate of 3.6 to 7.9% of lifetime production of a shale gas well that is directly emitted into the atmosphere as methane. This compares unfavorably (30% larger) to conventional wells, which range from 1.7 to 6%. When considering GWP over a 20-year horizon (in order to emphasize the time-sensitivity of emission reduction), shale gas has a 22%-42% larger greenhouse gas footprint than conventional gas. Shale gas does not compare favorably to either coal or oil, as its footprint appears to be 20% larger than that of coal (and 50% larger than oil) on a per-unit-of-energy basis. The 100-year horizon brings shale gas closer to the other fossil fuels in terms of footprint, but in most cases it is still larger than oil or coal.

This result contradicts conventional understanding of the fossil fuel landscape. While this analysis omits the health benefits gained from the cessation of coal use, the carbon advantage is less than advertised due to methane emissions. Howarth cites literature that places leakage thresholds (to make greenhouse gas footprint comparable to other fuels) at less than 2% to make shale gas better than oil and coal, a far cry from the 3.6 to 7.9% obtained. Methane emissions during the flow-back period can be reduced dramatically via appropriate technology, but the implementation of the technology is limited by existing infrastructure (or the lack thereof in certain places). If these estimates are borne out by measurements, than the impact of the shale gas revolution on the environment should be strongly reconsidered and policy should be redirected at reducing the fugitive methane emissions.

David Allen and his colleagues at the University of Texas at Austin measured direct methane emissions of shale gas at the production location (Allen et al. 2013). The group sampled 190 production sites which included 27 wells in the flow-back period, 4 well workovers, 9 in the well-unloading phase, and 150 in the post-completion production phase – all of 489 wells sampled were stimulated with fracking.

Allen's observations of the flow-back phase sites were in line with the conclusions of (Howarth, Santoro, and Ingraffea 2011) – the wells with the lowest flow-back emissions were those whose emissions went directly into a separator – "for those wells with methane capture or control, 99% of the potential emissions were captured or controlled". While other flow-back wells we flared or released directly into the atmosphere, they comprised only 33% of flow-back wells sampled and were observed to emit 0.55% the amount of an average flow-back well. The observations in (Allen et al. 2013) regarding unloading were similar – the paper finds that other studies have overestimated methane emissions, and that technology deployment drastically affects estimated and real emissions. The authors determine that this sample (the 9 wells he sampled averaged 1 metric tonne of methane emitted per unloading event, with an average of 6 unloading events per well per year) is too small to make national estimations, but that there is a large uncertainty bound in unloading emissions.

For post-completion well production, Allen et al. (2013) found that most leakage rates associated with equipment are roughly in line with EPA and Howarth estimates. However, he found geographical variation, noting that

> Emissions per pump from the Gulf Coast are statistically significantly different and roughly an order of magnitude higher than from pumps in the Midcontinent. Emissions per controller form the Gulf Coast are the highest and are statistically significantly different from controller emissions in the Rocky Mountain and Appalachian regions. Emissions per controller in the Rocky Mountain region are lowest and an order of magnitude less than the national average. (Allen et al. 2013)

In summary, the paper found that methane emissions from shale gas production were 0.42% of total production – significantly lower than the earlier estimates by Howarth and his colleagues. While Allen et al. measurements do not address potential losses in transport, storage, and distribution, replacing the estimates of Howarth et al. (2011) with their measurement counterparts lowers fugitive emissions rates to below 3.2% -- the level at which methane combustion provides a climate benefit over coal (Alvarez et al. 2012).

While the work in Allen et al. (2013) measured on site emissions, (Miller et al. 2013) use atmospheric concentrations of methane to infer anthropogenic emissions. This paper's observations were from different time period than Allen et al (2013), but his conclusion was that the EPA and other accounting bodies consistently underestimated methane emissions from fossil fuel extraction processes. Annual US anthropogenic methane emissions are estimated to be 1.5-1.7 times the EPA's estimation for 2007-2008, and Texas, Oklahoma, and Kansas accounted for 24% of methane emissions (Miller et al. 2013). While Allen et al. (2013) was wary of using atmospheric measurements to track fugitive methane, Miller et al. (2013) noticed an under-accounting of methane before the explosion of shale gas production from 2008 onwards. However, those measurements and estimates concern quantities of methane that are an order of magnitude smaller than those in Howarth et al. (2011) and Allen et al. (2013.

Gavin Heath and his colleagues (Heath et al. 2014) attempted to harmonize eight life-cycle analyses done by Howarth and others, reconciling the various results and units. He noted three challenges in this task: The type of gas studied (they all evaluated different unconventional gas resources, which is helpful to cover the diversity of resources in the country but difficult for harmonization purposes), the difference between "process-based" (scaling the individual activities of a well to a unit of energy, and then adding them together) and "cross-sectional" (taking all wells in a given area regardless of production phase and dividing them by the annual production from that area), and the manner in which the original authors compared their results to other fuel.

Harmonization of the studies had the primary effect of decreasing the estimates of lifecycle GHG emissions. The published estimates ranged from 437 to 758 g CO2e/kWh, and the magnitude of the adjustment ranged from +5% to -14%. Heath notes that "the most influential harmonization steps included thermal efficiency, recompletion adjustments, GWP, the inclusion of liquids unloading, and…transmission and distribution loss harmonization". Harmonization decreased the median difference between unconventional and conventional GHG footprints from +4% to +3%, with the median post-harmonization emissions being 465 g CO2e/kWh for shale gas and 461 g CO2e/kWh for conventional gas. This compares favorably to a harmonization of studies on coal-fired electricity generation, the median of which was 940 g CO2e/kWh. The estimate (758 g CO2e/kWh. 746 harmonized) in Howarth et al. (2011) is lower than the "best" coal plant (820 g CO2e/kWh) – however, Heath et al. (2014) note that these results were especially sensitive assumptions regarding liquids unloading. While Howarth noted that liquids unloading has been relatively uncommon in shale gas wells, Heath asserts that the largest gas GHG footprint estimates are accompanied by assumptions of high emissions from liquids unloading. Lastly, Heath et al. (2014) note that methane leakage rates ranged of 0.66% to 6.2% for shale gas – the variability (and the reason he did not use it for harmonization) is due mostly to differences in the aims of the studies. Other factors such as a given player, year, or operator may affect the rate, but there is limited data from which to draw solid conclusions (Heath et al. 2014). Harmonized estimates seem to support the results of Allen et al, who argues that the greenhouse gas footprint of shale sites is almost 50% smaller than those of coal. All of these calculations rely on a version of GWP, and there is growing literature that suggests a different (and perhaps better) way to look at emissions.

Allen[29] et al. argue that a major issue with the GWP approach to comparing greenhouse gases is the large degree of ambiguity accepted when setting policy targets for greenhouse gas emissions and warming. In the current approach, one can choose an upper limit of acceptable warming (which is nearly universally taken to be 2 C), settle on an associated carbon dioxide concentration and attempt to identify a level of greenhouse gas emissions that avoid exceeding the threshold. However, this requires the acceptance of a large amount of uncertainty with respect to the annual emissions and emissions rate required to meet and not surpass that threshold. On the other hand, it is possible base policy directly on a desired emissions target without explicit regard for atmospheric concentrations or temperature. With that approach, the uncertainty concerns the temperature response to the emissions target and the potential for variations in feedback as the climate changes.

Rather than choosing either of these, Allen proposes a way of looking at emissions that is more consistent with the likely emissions path. Setting a threshold emissions rate or temperature target (by setting a concentration threshold) may require readjusting thresholds in the case of overshoots until the emissions rate stabilizes. Allen assumes that fossils fuels will eventually phased out, and the emissions rate will follow this pattern: The emissions rate will increase for a time and then decrease until there is a sustainable negative emissions rate. These “containment scenarios” are useful if the integral of the emissions rate is bounded – that is to say that it is possible to put a temporal bound on emissions for a given amount of total emissions. Using this model, Allen finds that limiting emissions to a total of 2 trillion tonnes of carbon dioxide effectively dictates that all emissions occur before the year 2200. When considering total emissions of 1 trillion tonnes of carbon over the same time period, one of Allen’s model shows emissions peaking in the 2020s and decreasing afterwards.

This approach, which specifies a cumulative emissions target, also yielded insight into the connection between emissions and warming. Using multiple emissions scenarios and cumulative emissions levels Allen et al. found a positive relationship between peak (and less robustly, average) warming and cumulative carbon emissions, despite the differences in emission rates in the scenarios.

[29] Myles R. Allen, a different author from the one previously cited.

Despite the uncertainties within the scenarios, the results were both robust and supported by an independent model. The paper concludes that “total emissions determined peak CO_2-induced warming under a containment scenario [the scenario explained in the previous paragraph], not the peak emission rate or other details of the emission pathway”. This conclusion simplifies the emissions issue: regardless of the emissions pathway (how quickly we get there), a sensible goal is to limit cumulative emissions to a value associated with an acceptable warming level – 2 C. Allen finds that cumulative emissions limit to be 1 trillion tonnes of carbon by combining committed warming (based on past anthropogenic emissions) with “any future emissions pathway that is smooth, positive, and ends in exponential decline”. Thus assuming that emissions will peak and decline in the future, emitting less than 1 trillion tonnes of carbon (amongst all fossil emissions) is the best opportunity to avoid a level of warming greater than two degrees.

By uniting Allen’s view with GWP/GTP, one can see the unique problem with direct methane emissions. While there are many individual points to be debated with respect to the relative effects on global warming of both methane and CO_2, methane emissions remain important because the degradation of methane results in carbon dioxide. In the worst case scenario, methane has a demonstrably worse warming effect before decomposing into CO_2. In the best case scenario, methane remains in the atmosphere for too short a time to be significantly worse than CO_2 – either way, direct methane emissions bring us closer to the 1-trillion-tonne mark.

While measurements and harmonized estimates affirm traditional understanding of fossil fuels, the impact of fugitive methane is still being investigated. Disparities in data prevented it from being documented in the study, but the rise of shale gas production and the warming potential of methane portend its increasing importance. Heath called attention to potential issues accompanying a dearth regulation, noting that there are no rules or regulations (the EPA’s standards do not apply) that govern emissions from liquid unloading, which made a large difference in GHG footprint estimates. While regulation is far from centralized (most regulation is implemented on a state level), it is possible for the EPA and other federal government officials to take action with respect to environmental stewardship in oncoming era of energy independence.

Section 5: The New BLM Rules regarding Fracking

In March of 2015, the Bureau of Land Management[30] released its final rule on Hydraulic Fracturing on Federal and Indian lands. Going into effect on June 24, 2015, the rule complements existing regulations regarding development of oil and gas plays on federal land and serve as an update to previous rules. The rule has faced opposition from both environmental groups and the oil and gas industry. Some opposition is based on the perception that it constitutes an obstacle to further progression of a vital energy revolution, with the concern that the regulation will cost operators more than the government projects and discourage investment in locations where the rule applies. To this end, Wyoming filed a lawsuit against the Department of the Interior, contesting that 1) the BLM rule interferes with its ability to regulate fracking activities in the state, and 2) Under the Safe Water Drinking Act of 1974, only the Environmental Protection Agency has the authority to regulate any "underground injections."[31] Environmental groups criticize the weakness of the rule and its lack of an objective to decrease overall production in favor of promoting renewable energy.

The new rule takes a large stride into promoting further transparency with respect to fracking operations, particularly with respect to mandatory disclosure of chemicals used in the fracking process. Under the new rule, an operator of a fracking site on federal lands must complete (and document) the following:

1. Submit detailed information about the proposed operation, including, wellbore geology, the location of faults and fractures, the depths of all usable water, estimated volume of fluid to be used, and estimated direction and length of fractures, to the BLM.
2. Design and implement a casing and cementing program that follows best practices and meets performance standards to protect and isolate usable water[32].
3. Monitor cementing operations during well construction.
4. Take remedial action if there are indications of inadequate cementing, and demonstrate to the BLM that the remedial action was successful.

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[30] A subdivision of the Department of the Interior

[31] In 2003, a loophole was introduced into the SWDA to allow the use of benzene in fracking fluid by excluding hydraulic fracturing from the list of underground injections.

[32] Usable water: <10,000 PPM total TDS (total dissolved solids)

5. Performance a successful mechanical integrity test prior to the hydraulic fracturing operation.
6. Monitor annulus pressure during a hydraulic fracturing operation.
7. Manage recovered fluids in rigid enclosed, covered, or netted and screened above-ground storage tanks, with very limited exceptions.
8. Disclose the chemicals used to the BLM and the public, with limited exceptions for trade secrets.

The new rule addresses three major potential concern areas. It requires the full disclosure of all chemicals used in fracking fluid in basically all scenarios excepting those where the fluid is a proven trade secret. While several operators already disclose chemicals used under state and local disclosure laws, the rule hopes to set a standard that will eventually apply to all fracking operations. The rule also requires that operators adhere to best practices with respect to well casing, monitoring and testing them periodically throughout the construction and life of the well and fixing casing issues as they arise. Lastly, the rule specifies that waste water (flow-back) must be stored in above-ground storage tanks, excluding in-ground pits (as shown in figure 1) and prohibiting injection of flow-back into older wells. Further, limiting the containment infrastructure to storage tanks may eliminate a major pathway for dissolved methane to enter the atmosphere and leach into surrounding groundwater.

Perhaps the largest limitation of the rules is that which makes them possible in the first place – they only apply to federal and tribal lands, which are a relatively small portion of land and account for a minority of production, at about 10%. They have also been roundly criticized and challenged from both sides, making it difficult to discern and aim toward a particular goal.

Section 6: Conclusion

The shale gas revolution, along with the increasingly urgent issue of climate change, has changed the energy landscape of the world. The spread of fracking as a resource development technique has unlocked previously inaccessible resources, and in doing so has brightened the economic future of the U.S. and brought climate change-related issues to the forefront.

There is no doubt that shale gas has had a tremendous economic effect. On the municipal, county, and state scales it has stimulated economic activity by attracting investment from the natural gas industry. In turn, that has spurred growth in related industries and investment in infrastructure. On a national scale it has led natural gas to become the most produced fossil resource, modernizing power generation and showing promise as a transition fuel. On an international scale, it has paved the way for U.S. energy self-sufficiency and prompted investment in gas transportation technologies in anticipation of natural gas exports. The environmental benefits are tangible as well: as a replacement for coal, shale gas (and natural gas in general) decreases carbon emissions, avoids producing ash and other particulate manner, and obviates the need for environmentally damaging coal mining. However, shale-gas development brings its own set of issues and the boom has raised necessary questions regarding the future of energy, particularly as the reality of climate change has provided a way to evaluate its costs. It is necessary to weigh the present benefits of job creation and potential energy independence against the future issues aggravated by fossil fuel dependency. U.S. policy has sent a message that it believes natural gas to be the solution to its energy issues, but climate science all but demands an energy landscape dominated by renewable energy.

The question of fugitive methane is a particularly salient one, particularly when evaluating the environmental advantages of shale gas over coal. Estimates of process-based losses suggest that shale-gas production has a larger greenhouse gas emissions footprint than coal production, undermining conventional wisdom. On-site testing of shale developments revises those estimates downwards, making shale gas more carbon competitive than coal but identifying stages in the gas production process responsible for most emissions: well completion and liquids unloading. Further atmospheric analysis lands somewhere in the middle: the estimates of Howarth et al. (2011) may be too large, but methane emissions from natural gas production have been (and may continue to be) consistently underestimated. While these studies especially value methane as a greenhouse gas, the study by Allen et al. (2009) proposes the use of total carbon emissions as a better way to understand and act upon climate issues.

Before my research I significantly undervalued the impact of fugitive methane. I saw it as the cost of producing natural gas, particularly in the case of shale gas. What I did not realize was the degree to which fugitive methane can affect the carbon footprint – the harmonized estimates show that small changes in process calculation can drastically alter results. Equally valuable was learning about the potential for technological improvement – for example, installing infrastructure to capture flow-back reduces fugitive emissions from well completion by 99%. Technology that improves efficiency and protects the environment allows for resource exploration that does not disregard the future in favor of present benefits.

The final impression that I was left with was the size of the opportunity that exists for the U.S. In shale-gas, we find a resource that (for all intense and purposes) did not exist before, and there is enormous potential for economic growth via job creation and inexpensive energy. At the same time, however, there is an opportunity (and perhaps an obligation) to use this windfall to help alleviate the issues that continued fossil fuel dependency through this century will ultimately cause.

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