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Greenhouse Gas Emissions Associated with Projected Future Marcellus Shale Development

PSE Healthy Energy
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About PSE Healthy Energy
Physicians, Scientists and Engineers (PSE) for Healthy Energy is nonprofit research institute dedicated to supplying evidence-based scientific and technical information on the public health, environmental and climate dimensions of energy production and use. For more information on PSE Healthy Energy, visit www.psehealthyenergy.org

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1. Executive Summary

Drilling rates and average well production for Pennsylvania's Marcellus Shale grew exponentially between 2004 and 2011.[1] Depressed market prices due to over-production have since slowed new development, although there is considerable evidence to suggest a second "boom" is looming. Permitting records indicate growing demand for natural gas in the manufacturing and power sectors, as well as foreign markets, which can help to consume the current surplus and reduce constraints on market prices, thereby providing support for additional development. However, further development may have a high cost in terms of greenhouse gas (GHG) emissions.

Natural gas is predominantly made up of methane (75% to more than 96%), a GHG 86 times more powerful than carbon dioxide, integrated over a 20-year timeframe.[2] Natural gas systems are the largest source of anthropogenic methane emissions in the United States, as well as the third highest emitting source category for carbon dioxide emissions in the country.[3]

This report presents a fuel cycle accounting of GHG emissions associated with projected development of the Marcellus shale in Pennsylvania to 2045. Emissions are based on projected Marcellus production.

Key Findings

- Permitting records suggest a potential doubling of natural gas demand in the Marcellus consuming region;
- Low regional natural gas spot prices, relative to the national benchmark, favor Marcellus production for supplying new demand both within and outside of the region;
- We estimate that between 1,600 and 2,000 new wells per year will need to be brought into production to meet the expected demand growth;
- GHG emissions associated with this level of development are projected to peak at 654 to 816 MMt of CO_2e by 2025;
- Projected GHG emissions from Pennsylvania's natural gas sector in 2025 are at least three times higher than comparable emissions in 2012;
- Fugitive methane emissions account for 37% of total projected fuel cycle emissions, with combustion emissions making up the remainder.

Notes

1. DrillingInfo. 2015.

2. Myhre, G. et al. 2013. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., D. Quin, G.K. Plattner, M.Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midglet (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

3. EPA 2016.Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014. https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014.

1. Report Organization

This report presents a fuel cycle accounting of greenhouse gas (GHG) emissions associated with projected development of the Marcellus shale in Pennsylvania to 2045. Fuel cycle emissions include direct emissions from extraction/production, processing, and transport of a fuel, as well as end-use combustion of marketed fuel volumes (see Fig. 2.1).

Fuel cycle emissions from shale gas systems include vented and fugitive emissions of methane, and direct combustion emissions (carbon dioxide, methane, and nitrous oxide) associated with combustion of natural gas diverted from the fuel stream to power fuel cycle processes and end-use combustion of marketed production. Lifecycle emissions include additional combustion emissions associated with construction of wells and new infrastructure. These emissions are referred to as indirect or embedded emissions. Indirect emissions are generally insignificant relative to the fuel cycle emissions, accounting for less than one percent of full lifecycle emissions. As such, the primary focus of this report is direct fuel cycle emissions.

Projections of fuel cycle emissions of natural gas are based wholly on forecasted production rates, which in turn rely on estimates of field decline (i.e. decline in production over time assuming no new wells are drilled), well decline (i.e. the change in a well's production over time), and well life (i.e. how long a well will produce), as well as market constraints on further development. Since 2014, production from Pennsylvania's Marcellus shale has exceeded both local demand for natural gas and pipeline capacity to reach out-of-state markets. The resulting glut of natural gas has driven regional trade prices below the national benchmark spot price (i.e. Henry Hub Spot Price), and slowed drilling and completion activity across the Marcellus play. Recently permitted pipeline projects and end-user builds, however, indicate a significant growth in regional demand which may

► Abbreviations:

GHG - greenhouse gas

IPCC - Intergovernmental Panel on Climate Change

CO_2 - carbon dioxide

CH_4 - methane

N_2O - nitrous oxide

CO_2e - carbon dioxide equivalent

GWP - Global Warming Potential

EIA - U.S. Energy Information Administration

EPA - U.S. Environmental Protection Agency

PADEP - Pennsylvania Department of Environmental Protection

IMSP - Interior Marcellus Shale Play

MMt - million metric tonnes

Mcf - thousand cubic feet

Mcfd - thousand cubic feet per day

MMcf - million cubic feet

Bcf - billion cubic feet

Tcf - trillion cubic feet

GW - gigawatts (one billion watts)

stabilize market prices and spur a new development boom. The forecasted development and production rates presented in this report aim for low, moderate, and high increases in Marcellus production through 2045 assuming reported factors for Marcellus field and well decline and a 15-year well life.

Section 2 provides a brief introduction to relevant greenhouse gases and an overview of emission inventory methods, including emission sources and factors. In Section 3, we summarize the existing level of Marcellus development as of the end of 2014. Section 4 provides a detailed assessment of future development projections including new wells drilled, changes in field production, and assumptions regarding well life and estimated ultimate recovery per well. Fuel cycle emission results are presented in Section 5.

2. Quantifying Greenhouse Gas Emissions from Marcellus Shale Development

Greenhouse Gases

Greenhouse gases are naturally occurring atmospheric gases and anthropogenic emissions that absorb infrared radiation.[1] The Earth is continually absorbing immense amounts of solar radiation resulting in warming of its surface. The Earth releases some of this absorbed energy as infrared radiation, thereby cooling the surface. Greenhouse gas molecules in the atmosphere absorb the infrared radiation emitted from the Earth and will eventually re-emit it before it is either lost to space or absorbed by another greenhouse gas molecule. This ongoing cycle of absorption-emission-absorption maintains heat near the surface of the planet. In balance, naturally occurring greenhouse gases act to maintain relatively stable temperatures, which allows the Earth to sustain life. However, excessive concentrations of greenhouse gases trap too much radiation near the surface causing climate instability. The primary greenhouse gases are water vapor, carbon dioxide, methane, and nitrous oxide.

Carbon dioxide is the most commonly recognized greenhouse gas in part due to the enormous magnitude of anthropogenic carbon dioxide emissions and because it is responsible for the majority of warming that has occurred since the industrial revolution. Carbon dioxide can remain in the atmosphere and continue to act as a warming agent for hundreds of years.[3] However, trace atmospheric gases such as methane and nitrous oxide are much more efficient at trapping infrared radiation. Nitrous oxide is also long-lived in the atmospheric (~114 y), and, integrated over 20 years, is 268 times more warming than carbon dioxide. Methane, integrated over a 20-year time frame, is 86 times more efficient at trapping infrared radiation than carbon dioxide, but is removed from the atmosphere relatively quickly (~12 y). As a short-lived but powerful climate forcing agent, atmospheric methane can rapidly accelerate climate change. Likewise, mitigation of methane emissions can have nearly immediate climate benefits.[4]

Emissions from Natural Gas Systems

The dominant greenhouse gas emissions from natural gas systems are vented and fugitive methane losses and carbon dioxide emissions resulting from combustion of extracted natural gas both within the fuel supply chain and at market. Vented emissions are gas volumes purposely vented for safety and maintenance reasons. Fugitive losses are gas volumes unintentionally lost from the fuel cycle. Both vented and fugitive emission sources occur throughout the fuel cycle, including well heads, well site infrastructure, gathering lines, compressors, processing plants, transmission and storage systems, and

distribution systems. Additional emissions of methane and nitrous oxide also result from combustion, although quantities of these co-emissions are generally several orders of magnitude smaller than combustion emissions of carbon dioxide.[4,5] Full lifecycle emissions may include additional combustion emissions sourced from economic sectors outside of the fuel cycle. Figure 2.1 presents a generalized schematic of the natural gas fuel and lifecycles.

Vented and Fugitive Methane. Natural gas is predominantly made up of methane (75% to 96% or more) plus various proportions of higher hydrocarbons (e.g. ethane, propane, butane) and trace levels of non-hydrocarbon gases.[6] As such, vented and fugitive losses

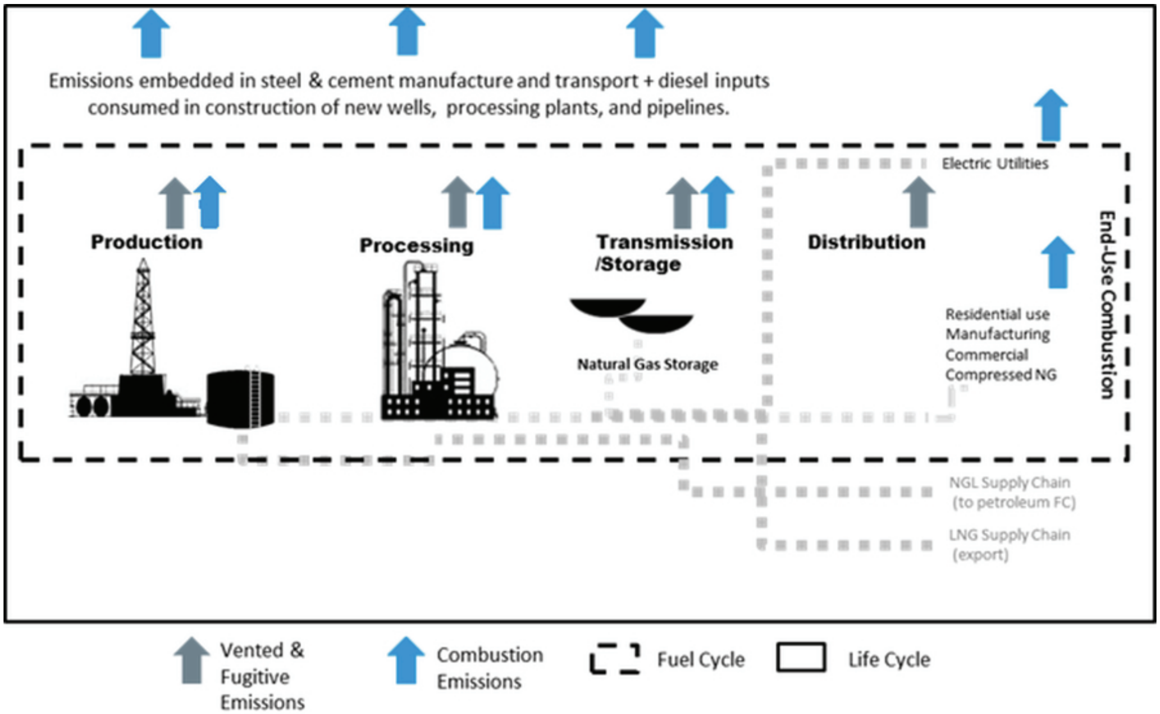
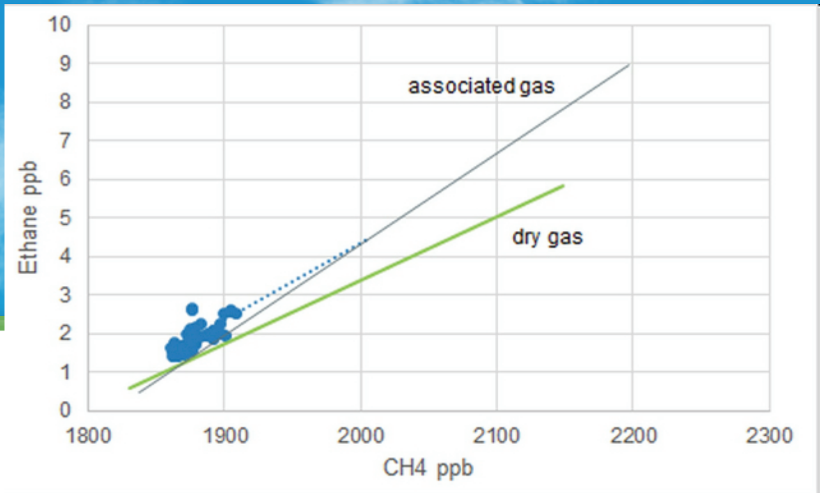


Figure 2.1. Natural Gas Fuel and Lifecycle Schematic. Fuel cycle GHG emissions include carbon dioxide, methane and nitrous oxide directly emitted during natural gas extraction, production, processing, transport and storage, distribution, and consumption by end-users. Full lifecycle emissions include indirect GHG emissions embedded in the infrastructure necessary to support fuel cycle processes, which are not included in the emissions inventory presented.

Figure 2.2. Comparison of Ratio of Atmospheric Ethane to Methane Concentrations for Typical Dry and Associated Gas, and Gas Emissions Measured (blue dots) in the Flight Path of Peischl et al. (2015). Ethane to methane concentrations as measured by Peischl et al. 2015 are heavier than expected for gas produced from the northeastern region of Pennsylvania (blue data points), which is characterized by dry gas production (green line). These emissions appear to reflect emissions from older conventional oil wells (grey line) located upwind of the sampling area, suggesting potential dilution of the Marcellus emissions.



from natural gas systems can have significant climate impacts. Estimates of methane loss rates rom natural gas systems, however, are not yet well constrained. Atmospheric sampling over several onshore resource plays across the conterminous United States show a wide range of fugitive methane losses from natural gas systems: from less than 1% to 17% or more of gross production. In 2015, we estimated a national weighted-average loss rate of 3.8% of gross natural gas production, based on peer-reviewed field-level measurements published up to the end of 2014 and weighted by the share of U.S. gross production for each study area.[7] More recently we've recalculated the national average, taking into account atmospheric measurements published since 2014 and revised our estimate of the weighted national average to 2.6% ±1.2%.[8]

We are aware of only three peer-reviewed atmospheric measurement campaigns specific to the Marcellus play in Pennsylvania. The first of these, Caulton et al. (2014),[9] sampled over the southwestern region of the state in 2011 and included a back trajectory analysis of air masses and emission sources contributing to the sampled area. Caulton et al. (2014) report fugitive losses attributable to natural gas systems of 9.8% (±7%) of gross production.[10] Two more recent studies report significantly lower fugitive losses (average of 0.39% ±0.1%) from natural gas production in the northern extent of the state (Peischl et al. 2015; Yuan et al. 2015).[11,12] However, sampling of Peischl et al. (2015) appears to be heavily influenced and diluted by upwind emissions from older oil fields of the north-central region of the state (Fig 2.2). Yuan et al. follow a similar flight path as that sampled by Peischl et al. (2015) in the Marcellus and report similar findings. Neither study presents a back trajectory of contributing air masses, so it does not appear that dilution from upwind sources was accounted for. As such, the relevancy of results from Peischl et al. (2015) and Yuan et al. (2015) to future Marcellus shale development is questionable. However, we also note that the emission factors for the southwestern corner of Pennsylvania, as calculated by Caulton et al., may not reflect emission profiles outside of the southwest region of the state. We, therefore, assume the national average loss rate of 2.6% for calculating methane losses from Marcellus production.

Fugitive emissions are calculated as the estimated mass of gross natural gas production lost multiplied by the fraction of methane contained in the production stream. Volume of production is converted to mass units assuming a natural gas density of 19.18 g/scf. Methane content for Marcellus gas is assumed to be 91.8%, reflecting an 80:20 mixture of dry (96% methane) and wet gas (75% methane) production.

The ratio of dry:wet gas production is based on the projected new well locations.[13] We use the PSU Marcellus Center map of the wet-dry gas boundary for the Marcellus Shale to categorize projected well locations.[14]

Combustion Emissions. Fuel cycle combustion emissions for natural gas systems are generally limited to those resulting from the combustion of plant/lease fuel and end-use combustion of marketed gas. Plant and lease fuel is the volume of natural gas diverted from the fuel stream to power well and processing plant infrastructure.[15] Marketed production refers to the volume of natural gas production remaining after plant and lease fuel is subtracted.[16] Additionally, fuel consumed in transmission and distribution of natural gas is, for calculation purposes, considered market production because any fuel contained in these systems

Table 2.1. Default Combustion Emission Factors (Source: Shires et al. 2009).

Combustion Emissions	Default
NG (pipeline) combustion HHV (g CO2/MJ)	50.300
NG (pipeline) combustion HHV (g N2O/MJ)	0.024
NG (pipeline) combustion HHV (g CH4/MJ)	0.077
NG (raw) combustion HHV (g CO2/MJ)	51.900
NG (raw) combustion HHV (g N2O/MJ)	0.024
NG (raw) combustion HHV (g CH4/MJ)	0.077

has been processed to pipeline quality and will, therefore, use the emission factor associated with processed and marketed natural gas. According to the U.S. Department of Energy data, the five-year average for raw natural gas consumed as plant/lease fuel is 4.8% of gross natural gas production.[17] Accounting for this and fugitive losses, the remaining 92.6% of gross production is combusted as marketed end-use fuels.

This calculation assumes that all marketed natural gas production is consumed in combustion. We do note that a small portion of natural gas production is diverted to the industrial sector as a chemical feedstock and therefore not combusted. In 2014, the U.S. industrial sector consumed 7.6 Tcf of natural gas,[18] with an estimated 7% of that being consumed as feedstock[19], or roughly 1% of the U.S. natural gas supply. Assuming that a similar percentage of Marcellus production is consumed as feedstock, we expect that the portion of natural gas production that is not combusted is inconsequential.

Lifecycle emissions additionally include indirect combustion emissions, or emissions embedded in the manufacturing and transport of raw materials and energy consumed in the construction of new wells and supporting infrastructure (e.g. wells, processing plants, pipelines). Embedded combustion emissions are generally insignificant relative to fuel cycle emissions.[20] We, therefore, focus our accounting on direct combustion

emissions only. In other words, emissions resulting from combustion of existing and new Marcellus natural gas production. Appendix I provides an overview of potential indirect combustion emission sources and accounting.

Default combustion emission factors for raw and pipeline quality gas are presented in Table 2.1.[21] Combustion emissions are calculated by multiplying the calculated volume of projected gross natural gas production combusted in each source category by the appropriate emissions factor. End-use combustion consumes pipeline quality gas. Upstream processes, i.e. plant and lease fuel diversions, are assumed to consume pre-processed or raw natural gas.

All emissions are converted to million metric tonnes of carbon dioxide equivalents per year (MMt $CO2e$ yr^{-1}) assuming IPCC (2015) reported global warming potentials for methane (86) and nitrous oxide (268), integrated over a 20-year time frame and inclusive of climate feedbacks.[22]

Notes

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4. Shires T.M. et al. 2009. Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry. Prepared by URS Corporation for the American Petroleum

5. EPA 2016. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014. https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014

Institute (API). API, Washington DC.

6. ibid.

7. PSE Healthy Energy. 2015. Science Summary: Climate Impacts of Petroleum and Natural Gas Systems. November 2015.

8. PSE Healthy Energy is currently drafting a four-part technical report synthesizing the last decade of peer-reviewed science on methane losses and climate change implications of methane.

9. Caulton D. et al. (2014). Toward a Better Understanding and Quantification of Methane Emissions from Shale Gas Development. PNAS. dx.doi.org/10.1073/pnas.1316546111

10. Ibid.

11. Peischl, J. et al. 2015. Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions, J. Geophys. Res. Atmos., doi:10.1002/

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12. Yuan, B. et al. 2015. Airborne flux measurements of methane and volatile organic compounds over the Haynesville and Marcellus shale gas production regions, J. Geophys. Res. Atmos. doi:10.1002/2015JD023242.n

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3. Existing Wells

The first Marcellus natural gas well completed with high-volume hydraulic fracturing was drilled in 2004 and brought into production a year later.[1] Within three years, more than 400 wells had been spudded in Pennsylvania's Marcellus shale.[2] By 2011, the spud count had risen to 4,800. However, not all spudded wells have been completed and brought into production. Between 2004 and 2011, on average, only 57% of new spuds contributed to production within the same timeframe (Fig 3.1). In more recent years, the number of wells brought to production has exceeded the number of spuds, indicating that some headway has been made in reducing the back-log of spudded wells. However, a large number of spudded wells remain not in production. As of 2014, our base year, PADEP records show roughly 8,400 wells spudded, with just 6,144 wells having ever reported production (Fig 3.1).[3]

New producing wells peaked in 2012-2013 at roughly 1,350 wells per year (Fig 3.1) and have since declined to a little over 1,000 per year as operators attempt to wait out low regional natural gas prices.[4,5]

Well quality, as indicated by average peak production, has also increased dramatically since 2005 and continues to be improving. Average peak production of Marcellus wells was less than 200 Mcfd in the early years of Marcellus development. By 2008, average peak production had

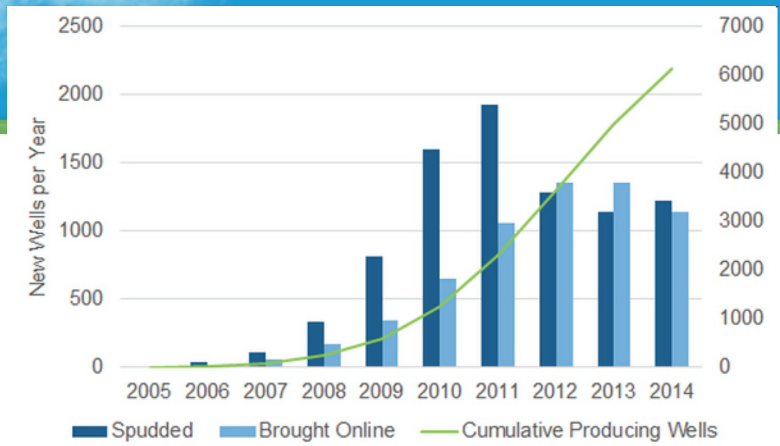

Figure 3.1 Growth of Marcellus Shale in Pennsylvania 2004-2014. (Source: DrillingInfo)

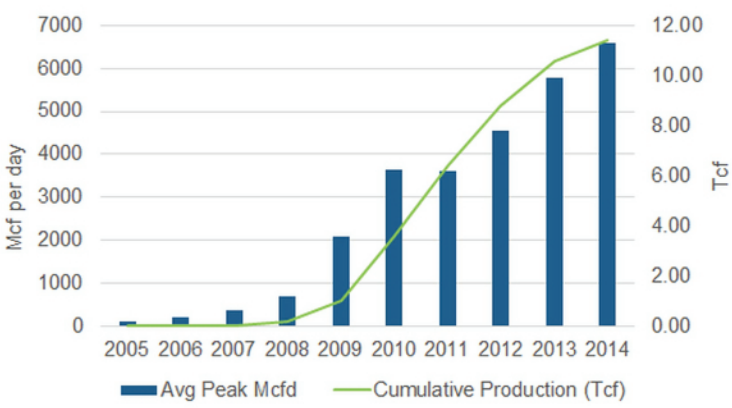

Figure 3.2. Average Peak Production (Mcfd) by Well Vintage and Cumulative Production (Tcf) in Pennsylvania's Marcellus play. (Source: Drilling Info)

climbed to almost 600 Mcfd. The increasing dominance of horizontal completions further boosted productivity, bringing average peak production up to ~3,600 Mcfd in 2010. Nearly every well drilled and completed in the Marcellus since 2011 has been a horizontal wellbore according to PADEP data, but well quality has continued to increase through intentional play optimization (e.g., extended lateral lengths, more frac stages, and changes to frac fluid chemistry). Peak production for wells completed in 2014 averages 6,585 Mcfd, based on DrillingInfo data (Fig 3.2). Cumulative production from Pennsylvania's Marcellus Shale at the end of 2014 totaled 11.4 Tcf.[6]

We estimate future production of existing wells as of the end of 2014 based on estimates of field-level decline for the Marcellus. The field-level decline reflects lost production from existing wells that must be replaced by new development to maintain or grow production levels. Hughes (2015) reports annual field decline of 32% for the Marcellus.[7] Given this rate of decline, we estimate production from existing wells will be almost completely depleted by 2025. However, existing wells will continue to contribute diminishing volumes through to 2045 (Fig 3.3). We assume no workovers or re-stimulations on existing wells that may increase their production. Production from newly constructed wells is expected to not only offset this production decline, but increase field production to meet growing natural gas demands.

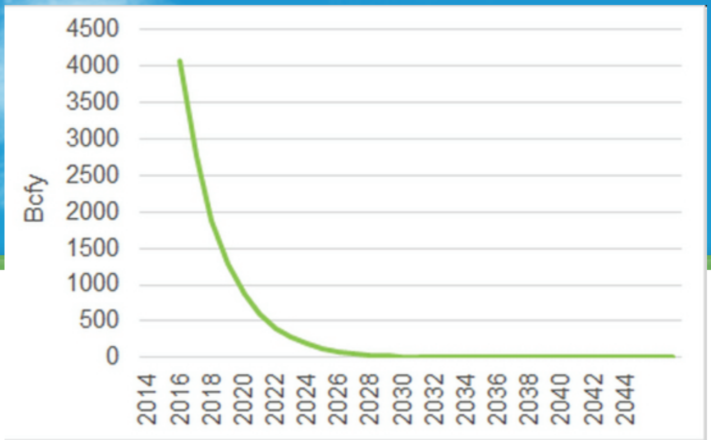

Figure 3.3. Sum of Production from Existing Wells to 2045. Projection assumes no new wells drilled or completed after 2014 and annual decline of 32%.

Notes

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2. "Spud" in this context refers to the first breaking of ground in well development and generally entails the setting of a short string of pipe (conductor casing, 80 - 180 ft) through unconsolidated sediment and soil to stabilize the overburden before commencing drilling. Conductor casing in Pennsylvania is typically driven in and cemented in place.

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4. http://www.eia.gov/todayinenergy/detail.php?id=18391

5. https://www.eia.gov/dnav/ng/hist/na1160_spa_2a.htm

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4. Projected New Development & Production

Despite recent sluggishness in new Marcellus development, there are signs of another drilling boom in the near future. The slowdown in Marcellus development in recent years is largely attributable to the price spread, which emerged in early 2014 in response to regional supply/demand imbalances, between Marcellus natural gas spot prices and the national benchmark (i.e. Henry Hub spot price).[1,2] The spread narrowed slightly in 2015 as pipeline capacity to move Marcellus production to consuming regions outside the shale basin increased. However, regional spot prices are still below the threshold for profitable development (Fig. 4.1).[3] Further development of the Marcellus over the next few decades will depend heavily on whether demand for Marcellus gas can keep pace with production and if transmission infrastructure is in place to deliver production to areas of new demand.

Permitting records indicate that demand for Marcellus gas, both locally and outside of Pennsylvania, is set to double by 2030. The main drivers of this increase are new natural gas demand in Pennsylvania's power sector and substantial growth in the state's pipeline take-away capacity. Pennsylvania's power sector is expected to bring 15.7 GW of new natural gas combined cycle capacity online by 2030.[4] We estimate throughputs to new and existing natural gas power plants at over 1,000 Bcfy by 2030, or almost three times 2014 levels (374.9 Bcf).[5] Additionally, the first methanol plant in Pennsylvania is expected to commence deliveries in 2017 with a committed throughput of 1.8 Bcfy.[6] Later expansions to the plant have been proposed, potentially bringing cumulative throughputs to 9.2 Bcfy, but are not firm.

Expansions and reversals of natural gas transmission pipelines are expected to increase access to Midwest and Northeast consuming markets and LNG export terminals along the Mid-Atlantic, Southeast, and Gulf coasts. EIA reports ten approved pipeline expansion and reversal projects due for completion between 2015 and 2017 with another ten projects in filing.[7] All total, assuming all pipeline projects are completed and an 80% utilization rate, new transmission pipelines represent additional deliveries of 2,788 Bcfy of natural gas to out-of-state markets, or an 87.6% increase relative to the state's 2014 interstate deliveries.

Table 4.1 presents estimates of future natural gas demand in Pennsylvania assuming timelines and volumes of gas consumed in the power and transmission projects presented. We assume no change from 2014 levels in non-Marcellus supplies and demand from the residential and commercial sectors. Based on these calculations, we estimate that production from Pennsylvania's Marcellus shale will need to reach at least 6,873 Bcfy by 2030, or increase by 77.2% relative to 2014 production.

Table 4.1. Estimated Natural Gas Demand (Bcfy) to 2030.

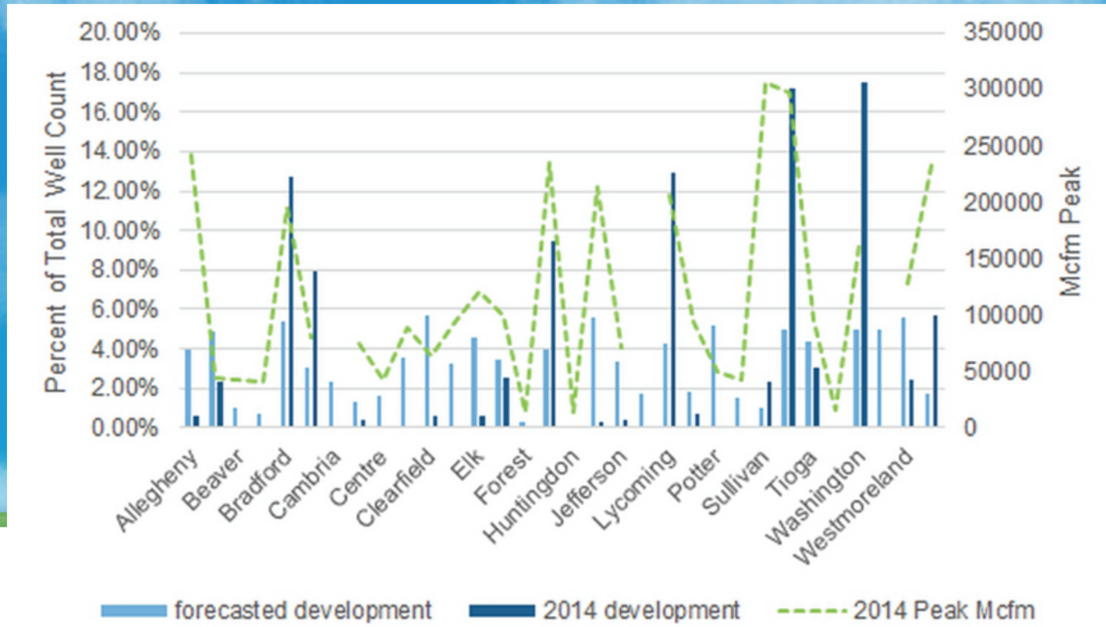
	2014	2020	2025	2030
Non Marcellus Net Dry Production*	101.2	101.2	101.2	101.2
Supplemental gas	0.0	0.0	0.0	0.0
Interstate Receipts	444.1	444.1	444.1	444.1
Storage Withdrawals	384.3	384.3	384.3	384.3
Marcellus Net Dry Production*	3878.7			
Total Supply	**4808.3**	**929.6**	**929.6**	**929.6**
Sum In-state Deliveries	-1004.2	-1642.7	-1642.7	-1729.4
Residential & Commercial Demand	*-400.4*	*-400.4*	*-400.4*	*-400.4*
Power Sector Demand†	*-374.9*	*-1011.6*	*-1011.6*	*-1098.2*
Industrial Demand‡	*-229.0*	*-230.8*	*-230.8*	*-230.8*
Interstate Deliveries§	-3184.0	-5971.7	-5971.7	-5971.7
Total Demand	**-4188.1**	**-7614.5**	**-7614.5**	**-7701.1**
Marcellus Production to Balance	-519.0	6786.0	6786.0	6872.7

**Net production equal dry production minus volumes consumed as lease, processing, and pipeline fuel.*
†Power sector demand includes approved 15.7 GW of additional NGCC capacity through 2030
‡Industrial demand includes additional 1.8 bcfy committed to the Primus Green Energy (PGE) methanol plant to be built in Pennsylvania and slated for deliveries in 2017
§Interstate deliveries include increased take-away pipeline capacities through to 2017. Throughput volumes assume a utilization rate of 80%.

In this section, we model various rates of future development with the aim of meeting or exceeding our estimates of demand growth. We do not explicitly account for geologic or technological constraints on recoverable resources. Additionally, we assume that economic constraints on development are released as intra- and interregional demand increases and infrastructure to support the new demand is put in place to support further development.

New Wells. Our mid-range estimate of development rates is inferred from an earlier assessment of future development across the Interior Marcellus Shale Play (IMSP).[8] That analysis predicted an additional 66,000 new wells drilled across the IMSP states (West Virginia, Maryland, Ohio, Pennsylvania, and New York) based on 2013 estimates of lifetime production for an IMSP well (1.9 Bcf) and technically recoverable resources of 144 Tcf from EIA. Hanson et al. (2016) spatially allocated their basin-wide estimate of new wells based on landscape analysis of developable areas. The analysis did not account for existing political or economic limits on development such as moratoria, bans, or market prices.[9] Roughly 72% of new IMSP wells, according to their analysis, are expected to be drilled in Pennsylvania, or 47,600 new wells statewide over the next three decades. This equates to an annual drilling and completion rate of roughly 1,600 new wells a year.

Figure 4.1 Comparison of 2014 and Forcasted Development to 2045 by County. New wells (clustered columns) are presented as a percent of the total new wells completed in 2014 or projected to be completed by 2045. Dashed lines reflect the average peak production per well for a given county. Not all counties have data available on peak production.



We constrain our mid-range estimate using historic Marcellus development activity in Pennsylvania. At the height of Pennsylvania's Marcellus "boom," spudding rates in the state had reached nearly 2,000 new spuds per year. However, a significant portion of these new spuds were shut-in to postpone production, as operators waited for supporting infrastructure and better market pricing (Fig. 3.1). Our estimate of future demand is expected to release these constraints on development and allow for maximum development. On the other hand, competition with emerging plays may limit access to drilling and completion equipment and, therefore, limit development rates. We use Marcellus peak drilling activity (2,000 wells per year) as our high-range estimate of potential development. Well completions peaked at just 1,350 wells and reflect potential constrained development.[10] We discount this constrained rate of development to provide an equal distance between the mid-range estimate (1,600 wells per year) and the bounding extremes for a low-range estimate of 1,200 wells per year. Total projected wells drilled and completed over three decades equal 36,000, 48,000, and 60,000 for Low-, Mid-, and High-development scenarios, respectively.

New Production. All calculations for production (q) from new wells over time is calculated assuming a standard hyperbolic decline (equation 4.1).[11]

$q = q_i(1 + bD_it)-1/b$ **(Equation 4.1)**

Where:

q_i = peak production

b = hyperbolic exponent

D_i = initial nominal decline rate

t = time in months

Assumed peak production rates can greatly impact estimates of field production, as well as estimated ultimate recovery per well. Peak production rates have increased in recent years due to optimized fracture and completion design resulting in better initial well quality. Well data indicate a 33% increase in average peak production rates for Marcellus wells drilled in 2013 (~4,000 Mcfd), compared to wells drilled just a year earlier (~3,000 Mcfd).[12] More recent data suggest rates of 7,000 to more than 9,000 Mcfd in some the northeastern counties.[13] By the end of 2014 the weighted average peak production across the state was in excess of 6,000 Mcfd,

according to DrillingInfo data.[14] However, 80% of the new wells brought online in 2014 were located in the highly productive core areas of the northeast and southwest corners of the play, which are already heavily developed (Fig. 4.1). State average peak production rates are likely to decline as future development increasingly moves into more marginal areas of the interior play.

We weight county statistics on peak production per well to the percentage of wells forecasted to be drilled in each county.[15] Peak production values assume 2014 data from the DrillingInfo database.[16] We supplement this dataset with 2013 data reported in Swindell (2016) for counties with no new wells reporting in 2014.[17] Based on this calculation, we estimate an average peak production rate of 4,150 Mcfd. We assume an initial nominal decline rate of 5% per month, based on production records for Pennsylvania Marcellus wells,[18, 19] and a hyperbolic exponent of 0.6.[20] Our assumed initial production and decline curve calculations result in an estimated ultimate recovery for each well of 4.5 Bcf over 15 years, a value more than twice that of the 1.9 Bcf per well Hanson et al. (2016) assumed in their estimates of future well counts, but within the range of current estimates for the Marcellus.[21]

Projected annual production from Pennsylvania Marcellus wells peaks in 2022 at 4.8, 6.3, and 7.8 Tcf for the Low-, Mid-, and High scenarios, respectively, reflecting production increases of 13.8% to 88.8% relative to 2014. By comparison, the production goals we set to meet permitted demand are 6.8 Tcf for 2022 (Table 4.1), a

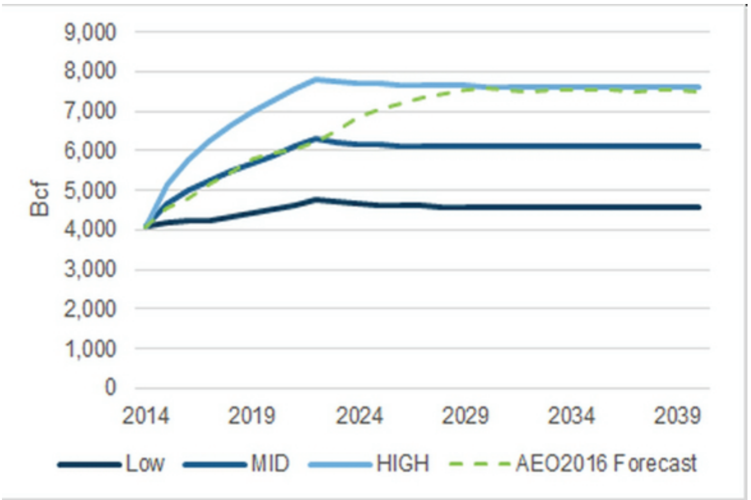


Figure 4.2. Projected Natural Gas Production from Pennsylvania's Marcellus Shale to 2045.

value between the Mid- and High-development scenarios. Therefore, based on estimated future demand volumes, we expect ongoing development of the Marcellus shale in Pennsylvania to require an additional 1,600 and 2,000 new wells brought into production annually. This estimate is comparable to EIA projections to 2040 (Fig. 4.2).[22]

Notes

1. http://www.eia.gov/todayinenergy/detail.php?id=18391

2. EIA. 2012. Natural Gas Explained - Factors Affecting Natural Gas Prices.
www.eia.gov/energyexplained/index.cfm?page=natural_gas_factors_affecting_prices.

3. Marcellus HH spot price + profitable price

4. PSE. 2017. Climate Impact of CPP Compliance Scenarios and New Natural Gas-Fired Capacity in Pennsylvania (in print)

5. EIA EIA-923 Monthly Generation and Fuel Consumption Time Series File, 2016 June

6. Methanol has traditionally been used in acetic acid and formaldehyde production; other uses include transportation fuels, fuel blending, and feedstock in production of dimethyl ether, olefins, and other chemicals. More information on methanol uses and demand forecasts is available at http://www.methanolmsa.com/mmsa-database/methanol-and-derivatives-analysis-2016-client-access/

7. https://www.eia.gov/naturalgas/pipelines/EIA-NaturalGasPipelineProjects.xls

8. Hanson, L. et al. 2016. The Potential Environmental Impact from Fracking in the Delaware River Basin. IRM-2015-U-011300. CNA Corporation. Arlington, VA, USA.

9. Ibid.

10. http://www.dep.pa.gov/DataandTools/Reports/Oil%20and%20Gas%20Reports/Pages/default.aspx

11. Holdaway, K.R. et al. 2015. Unconventional Data-Driven Methodologies Forecast Performance In Unconventional Oil and Gas Reservoirs. Paper 1910-2015. SAS Conference Proceedings: SAS Global Forum 2015. April 26-29, 2015, Dallas, TX, USA.

12. DrillingInfo. 2015.

13. Swindell, G.S. 2016. Marcellus Shale in Pennsylvania: A 3,800 Well Study of Estimated Ultimate Recovery (EUR). March 2016 Update. Gary S. Swindell Petroleum Engineering.

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15. Hanson, L. et al. 2016. The Potential Environmental Impacts of Full-development of the Marcellus Shale in Pennsylvania. IRM-2016-U 013695. CNA Corporation. Arlington,VA, USA.

16. DrillingInfo, 2015

17. Swindell, G.S. 2016. Marcellus Shale in Pennsylvania: A 3,800 Well Study of Estimated Ultimate Recovery (EUR). March 2016 Update. Gary S. Swindell Petroleum Engineering.

18. http://www.dep.pa.gov/DataandTools/Reports/Oil%20and%20Gas%20Reports/Pages/default.aspx

19. DrillingInfo, 2015.

20. Swindell, G.S. 2016. Marcellus Shale in Pennsylvania: A 3,800 Well Study of Estimated Ultimate Recovery (EUR). March 2016 Update. Gary S. Swindell Petroleum Engineering.

21. Ibid.

22. EIA (2016). Annual Energy Outlook

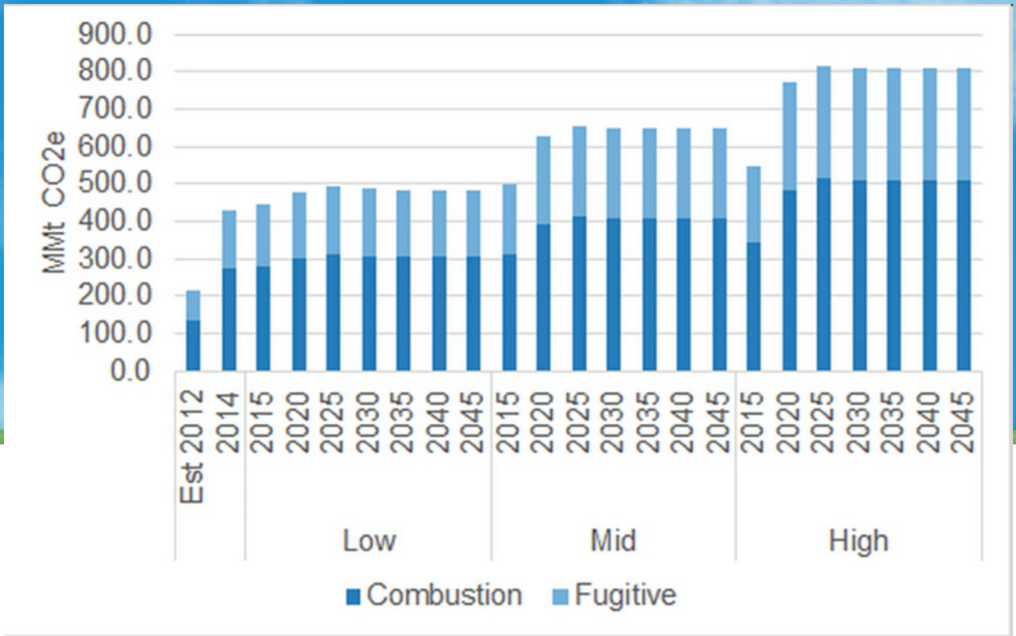

Figure 5.1 Projected Fuel Cycle Emissions Associated with Past, Current, and Future Development of the Marcellus Shale for three scenarios.

5. Results and Conclusions

Emissions

Based on the projected production levels for Mid-, and High- development scenarios, we estimate natural gas fuel cycle emissions associated with future Marcellus shale development of 647.6 to 809.5 MMt CO2e y^{-1} by 2045 (Fig 5.1). As with production, peak emissions are expected before 2025 with rate of 653.8 to 815.7 MMt CO2e y^{-1}. Emissions from end-use combustion of marketed gas are calculated on energy content basis and do not account for efficiencies at power plants. Emissions in 2045 reflect a 49.9% to 87.3% increase in emissions from natural gas systems, relative to 2014.

Recent federal climate change mitigation strategies set goals relative to 2012 emissions, so we also compare projected emissions to estimates of Pennsylvania's emissions from natural gas sector in 2012 (Fig. 5.1). We estimate greenhouse gas emissions associated with Pennsylvania's natural gas production for 2012 using the same methodology described in Section 2 and historic production data.[1] Projected fuel cycle emissions in 2045 are at least three times the estimated emissions from the state's natural gas systems in 2012.

Conclusions

Based on a limited set of permitting records, we estimate that Marcellus production will need to almost double by 2030 relative to 2014 levels, to meet expected growth in regional natural gas demand. To achieve and sustain this level of production will require the addition of more than 1,600, but less than 2,000 new wells a year. This rate of development would constitute a second drilling "boom."

Total fuel cycle emissions associated with this level of development are projected to reach 654 to 816 MMt CO2e by 2025. These emissions reflect an increase in climate emissions from natural gas systems, relative to 2014 levels, of 50% to 87%, and are at least three times that of 2012 emissions from Pennsylvania's natural gas sector.

We note that development projections presented here are based on numerous simplifying assumptions, including a

constant rate of development over time and stable peak production per well over time and space. In reality, development will respond and adjust to changes in the economic, regulatory, technological, and geologic environments. As such, we urge caution in interpreting these results. The development scenarios presented are intended to illustrate the potential range of emission scenarios associated with future Marcellus shale development in Pennsylvania given recent permitting activity and current technology and field characteristics.

Notes

1. https://www.eia.gov/dnav/ng/hist/na1160_spa_2a.htm

Appendix I: Indirect Emissions

New construction of wells and supporting infrastructure results in additional indirect emissions not accounted for in the main analyses of this report. These emissions reflect the diesel fuel and materials consumed in infrastructure installation after 2014. Indirect emissions typically represent a relatively small percent (≤1%) of total annual lifecycle emissions. Here, we provide an estimate of indirect climate emissions associated with projected production increases from the High-development scenario (2,000 wells per year)

Well Construction: Indirect combustion emissions related to well construction account for energy inputs consumed in constructing a shale well, including inputs attributable to manufacture of the steel and concrete consumed in well construction and diesel fuel consumed in transport vehicles and drilling rig engines. NETL calculations apportion energy and material flows by mass of natural gas production over the full life of the well, assuming 0.02 kg per scf of natural gas.[1] Our well projections estimate lifetime production per well of 4,541.3 MMcf, or roughly 87 thousand tonnes of natural gas produced per well. Total emissions from new well construction for every 2,000 wells are allocated across the well life time (15 years) to allow for fair comparison with fuel cycle emissions.

Processing Capacity: Processing capacity in the Marcellus region has surged in recent years, with an estimated construction and installation of at least 4.1 Bcfd new capacity since 2011 and another 1,000 MMcfd in capacity in planning.[2] The adequacy of existing processing capacity in meeting the throughput demands of project production is assessed by comparing state and regional processing capacity with projected wet gas production from existing and new wells. Dry gas production has a high enough methane content to meet pipeline standards and does not require processing.

Total processing capacity in 2014 is reported as 4,484 MMBcfd, and includes 13 facilities in Pennsylvania and 8 West Virginia plants located along the Pennsylvania border.[3] EIA reports that these plants processed 3,011 MMcfd in 2014; of this, 2,230 MMcfd was sourced from Pennsylvania's Marcellus wet gas wells (wet gas production in 2014), or 74% of total throughputs. We, accordingly, adjust total available processing capacity by subtracting the difference in processing flows (782 Mmcfd). This method thereby assumes that regional throughputs produced from plays other than Pennsylvania's Marcellus shale remain stable throughout the study period. Table A1.1 presents cumulative regional processing capacity available for Marcellus wet gas produced in Pennsylvania overtime.

Table A1.1. Balance of Natural Gas Processing Capacity Available for Future Development of Pennsylvania's Marcellus Shale.

	2014 Capacity (MMcfd)	2016 New Capacity (MMcfd)	Additional Planned Capacity (MMcfd)
Cumulative Capacity	4484.00	5484.5	6484.50
Non-Marcellus Flow	-782.00	-782.00	-782.00
Adjusted Cumulative Capacity	**3702.00**	**4702.50**	**5702.50**

Development projections forecast peak wet gas production of 4,183 MMcfd in 2030, assuming the High development scenario. This leaves a maximum capacity shortage of 481 MMcfd, or roughly half of the 2016 capacity expansions.[4]

We are not aware of any published emission factors for construction of a natural gas processing plant and associated raw material consumption. Beath et al. (2014) model an average 200 MMcfd capacity gas plant and estimate that steel requirement of 9.5 tonnes per MMcfd.[5] No data could be found for other materials consumed in new plant construction or expansion projects. Similarly, no data was found for estimates of diesel consumed in construction and transport of materials. Steel emissions are estimated at 1.7 tonnes carbon dioxide per tonne of steel.

New Pipelines: New pipeline installations include both gathering lines and transmission lines. The emission factor for pipeline installation are taken from the NETL Unit Process Library and includes exhaust emissions from heavy equipment and transport of pipes.[6] Mass of steel consumed in pipeline installation is based on pipeline characteristics presented in McAllister (2002).[7] Steel manufacturing emits 1.74 tonnes CO2 per tonne of steel.[8]

Hanson et al. (2016) estimated new gathering line requirements of 0.98 miles per well pad (8 wells per pad).[9] For our High development scenarios (2,000 wells per year), this equates to 245 miles of new gathering lines. Calculations for mass of steel consumed by gathering lines assume a steel density of 169.1 tonne/mile based on a 18" diameter and thickness of 0.375". Total steel in new gathering lines is estimated at 41.4 thousand tonnes.

EIA records indicate an additional 1,808 miles of new and expanded transmission lines and laterals since 2014.[10] Calculations for mass of steel consumed assume steel density of 284.2 tonne/mile based on a diameter of 30" and thickness of 0.375". Total steel in new transmission lines is estimated at 555 thousand tonnes.

Indirect emissions associated with pipeline installation and material manufacturing are allocated annually assuming a 30-year equipment life.

Emissions: Table A2.2 presents inputs and estimated emissions from well and pipeline construction. Total indirect emissions are estimated at 0.21 MMt CO2e per year, or roughly 0.03% of the average annual fuel cycle emissions for the HIGH development scenario (800 MMt CO2e).

Table A2.2. Estimated Indirect Emissions from Well and Pipeline Construction.

Natural Gas Well Construction and Installation							
Parameter		**Factor**	**Unit**	**Tonnes**	**GWP**	**Lifetime**	**MMt/y**
	CO2	1.54E-02	tonne/tonne	8.65E+04	1	15	1.78E-01
	CH4	8.41E-07	tonne/tonne	8.65E+04	86	15	8.34E-04
	N2O	0	tonne/tonne	8.65E+04	268	15	0.00E+00
	Sum						1.78E-01
Pipeline Construction and Installation							
Parameter		**Factor**	**Unit**	**Miles**	**GWP**	**Lifetime**	**MMt/y**
	CO2	34.3	tonnes/mile	2053	1	30	2.35E-03
	CH4	0.00155	tonnes/mile	2053	86	30	9.12E-06
	N2O	0.000695	tonnes/mile	2053	268	30	1.27E-05
	Sum						2.37E-03
Pipeline, Steel Manufacturing							
Parameter		**Factor**	**Unit**	**Tonnes**	**GWP**	**Lifetime**	**MMt/y**
	Pipeline	1.7	tonne/tonne	555235	1	30	3.15E-02
	Processing	1.7	tonne/tonne	4566	1	30	2.59E-04
Total Indirect Emissions							2.13E-01

Notes

1. NETL (2013). NETL Life Cycle Inventory Data - Unit Process: Natural Gas Well Construction and Installation, Construction. U.S. Department of Energy, national Energy Technology Laboratory. Last Updated: February 2013 (version 01).

2. EIA. 2014. http://www.eia.gov/cfapps/ngqs/ngqs.cfm?f_report=RP9

3. Ibid.

4. Expansions reported on MarkWest, Elk Horn, and Blue Racer Midstream web sites

5. Beath et al. 2014. Contribution of Infrastructure to Oil and Gas Production and Processing Carbon Footprint. Argonne National Laboratory, Energy Systems Division Systems Assessment Group. Argonne IL, USA.

6. NETL. 2010. NETL Life Cycle Inventory Data - Unit Process: Onshore Pipeline Installation and Deinstallation. US Department of Energy, national Energy Technology Laboratory. Last Updated: January 2010 (version 01)

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9. Hanson et al. 2016. The Potential Environmental Impact from Fracking in the Delaware River Basin. IRM-2015-U-011300. CNA Corporation. Arlington, VA, USA.

10. EIA. 2015. http://www.eia.gov/naturalgas/pipelines/EIA-NaturalGasPipelineProjects.xls

Appendix II: Data Sheets

The following tables present the projection data used in this assessment.

Production, Existing Wells MMcf/y

Natural Gas Type	2014	2015	2016	2020	2025	2030	2035	2040	2045
Wet Gas (20%)		553,573	376,430	80,486	11,702	1,701	247	36	5
Dry Gas (80%)		2,214,292	1,505,719	321,943	46,808	6,806	989	144	21

Production, New Wells MMcf/y

Scenario	Natural Gas Type	Wells/y	2015	2016	2020	2025	2030	2035	2040	2045
LOW	Wet Gas (1200 wells/y)	240	286,895	468,690	824,369	914,979	914,979	914,979	914,979	914,979
MID	Wet Gas (1600 wells/y)	320	382,527	624,920	1,099,159	1,219,972	1,219,972	1,219,972	1,219,972	1,219,972
HIGH	Wet Gas (2000 wells/y)	400	478,158	781,151	1,373,949	1,524,965	1,524,965	1,524,965	1,524,965	1,524,965
LOW	Dry Gas(1200 wells/y)	960	1,147,580	1,874,761	3,297,477	3,659,916	3,659,916	3,659,916	3,659,916	3,659,916
MID	Dry Gas (1600 wells/y)	1280	1,530,107	2,499,682	4,396,637	4,879,888	4,879,888	4,879,888	4,879,888	4,879,888
HIGH	Dry Gas (2000 wells/y)	1600	1,912,633	3,124,602	5,495,796	6,099,859	6,099,859	6,099,859	6,099,859	6,099,859

Total Production (MMcf/y)

Scenario		2014	2015	2016	2020	2025	2030	2035	2040	2045
LOW	1200 wells/y	4,070,390	4,202,340	4,225,600	4,524,276	4,633,405	4,583,402	4,576,131	4,575,074	4,574,921
MID	1600 wells/y	4,070,390	4,680,499	5,006,751	5,898,225	6,158,370	6,108,366	6,101,096	6,100,039	6,099,886
HIGH	2000 wells/y	4,070,390	5,158,657	5,787,901	7,272,174	7,683,335	7,633,331	7,626,061	7,625,004	7,624,850

Total Production (MJ/y)

Scenario		2014	2015	2016	2020	2025	2030	2035	2040	2045
LOW	1200 wells/y	4.40E+12	4.54E+12	4.56E+12	4.89E+12	5.00E+12	4.95E+12	4.94E+12	4.94E+12	4.94E+12
MID	1600 wells/y	4.40E+12	5.05E+12	5.41E+12	6.37E+12	6.65E+12	6.60E+12	6.59E+12	6.59E+12	6.59E+12
HIGH	2000 wells/y	4.40E+12	5.57E+12	6.25E+12	7.85E+12	8.30E+12	8.24E+12	8.24E+12	8.24E+12	8.23E+12