NOTA DI LAVORO

17.2015

The Economics of Shale Gas Development

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Energy: Resources and Markets
Interim Series Editor: Matteo Manera

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Summary

In the past decade, innovations in hydraulic fracturing and horizontal drilling have fueled a boom in the production of natural gas (as well as oil) from geological formations – primarily deep shales – in which hydrocarbon production was previously unprofitable. Impacts on U.S. fossil fuel production and the U.S. economy more broadly have been transformative, even in the first decade. The boom has been accompanied by concerns about negative externalities, including impacts to air, water, and quality of life in producing regions. We describe the economic benefits of the shale gas boom, including direct market impacts and positive externalities, providing back-of-the-envelope estimates of their magnitude. The paper also summarizes the current science and economics literatures on negative externalities. We conclude that the likely scope of economic benefits is extraordinarily large, and that continued research on the magnitude of negative externalities is necessary to inform risk-mitigating policies.

Keywords: Hydraulic Fracturing, Economic Benefits, Positive Externalities, Negative Externalities, Environmental Impacts
JEL Classification: Q4, Q42, Q5

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Keywords: hydraulic fracturing, economic benefits, positive externalities, negative externalities, environmental impacts

Abstract

In the past decade, innovations in hydraulic fracturing and horizontal drilling have fueled a boom in the production of natural gas (as well as oil) from geological formations – primarily deep shales – in which hydrocarbon production was previously unprofitable. Impacts on U.S. fossil fuel production and the U.S. economy more broadly have been transformative, even in the first decade. The boom has been accompanied by concerns about negative externalities, including impacts to air, water, and quality of life in producing regions. We describe the economic benefits of the shale gas boom, including direct market impacts and positive externalities, providing back-of-the-envelope estimates of their magnitude. The paper also summarizes the current science and economics literatures on negative externalities. We conclude that the likely scope of economic benefits is extraordinarily large, and that continued research on the magnitude of negative externalities is necessary to inform risk-mitigating policies.

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1.0 INTRODUCTION

In the latter part of the 20th century, a small group of determined entrepreneurs (supported by decades of federal and private research and development investments) chased a dream – that they would be able to extract meaningful, economically valuable amounts of natural gas from shale deposits (Zuckerman 2013). These individuals were broadly ridiculed at the start, but when their determination paid off and large amounts of gas began to flow from the wells they had drilled, critics in the industry changed their tune. The methods used to unlock these enormous deposits include hydraulic fracturing, or “fracking"– the injection of water under high pressure to fracture low-permeability shale – along with horizontal drilling. Both techniques had been used in the past; fracking was used commercially as early as 1950, and horizontal wells were common by the late 1970s (King 2012). But innovations in their joint use proved the key to unlocking massive stores of natural gas, which have transformed important parts of the U.S. economy.

The substantial increase in economically recoverable reserves, mostly thus far in North America, has led to lower prices for residential and commercial consumers, increased reliance on natural gas to generate electricity, and increased reliance on natural gas as an input to industrial production (U.S. Energy Information Administration 2011, 2014a). As abundant shale gas displaces coal in electricity generation and other industrial uses, the shale boom could also have positive implications for local air pollution and the greenhouse gas emissions that are changing the global climate. At the same time, concerns have been raised about the potential for fracking’s water intensity to place pressure on agricultural and municipal use of fresh water, as well as aquatic ecosystems. The chemicals added to the water before fracking, as well as significant wastewater produced, have prompted worries about the contamination of aquifers, rivers, and streams. Air quality impacts from the practice have also been highlighted by its opponents, as have “boomtown” disamenities such as crime and traffic congestion.

In this paper, we describe the potential benefits and costs associated with the widespread adoption of this important gas production method. To this end, we detail the effects described above, along with others, to provide as complete and current a picture as feasible concerning its economic and public policy implications. The paper is broken into sections on the benefits of shale gas development, and the costs of shale gas development, with both sections including direct market impacts and externalities. While our main focus is on shale gas, fracking has also unlocked vast stores of oil from low-permeability formations; where possible, the paper mentions the implications of this additional application for fracking’s benefits and costs.

2.0 THE BENEFITS OF SHALE GAS DEVELOPMENT

2.1 Direct market impacts

With the surge in fracking and horizontal drilling, oil and gas production in the U.S. has increased dramatically during the last decade. Annual shale gas production in the U.S. grew from about 1 trillion cubic feet (Tcf) in 2006, to about 9.7 Tcf in 2012, and is expected to grow to about 19.8 Tcf by 2040; shale gas in 2014 comprises more than 40% of total U.S. natural gas production (U.S. Energy Information Administration 2014a).

Figure 1 plots the natural gas production from the major emerging shale plays in the U.S. since January 2007, in billion cubic feet per day (Bcf/day).[1] Apart from the Haynesville play, which increased dramatically from 2009 to 2012, and then went into decline, there are consistent increases in production over this time frame.[2] The Marcellus play has witnessed particularly impressive production increases since 2007.[3]

2.1.1 Increases in consumer surplus from lower prices

The substantial increase in natural gas production over the past several years induced clear benefits to consumers. Because supply has increased and the equilibrium price of gas has fallen, consumer surplus is doubly enhanced. To be sure, the increased supply lowers home heating costs during the winter, but it induces year-long benefits. As its cost falls, natural gas has become an increasingly important fuel for electricity generation; this expansion in the supply of inputs into the electricity market lowers costs to gas-fired electricity producers as well as electricity prices for consumers (Linn et al. 2014b). Lastly, the expanded supply of natural gas, and attendant reduction in price, have facilitated its role as an input into a variety of industrial production processes, which generates far-reaching economic benefits (U.S. Energy Information Administration 2014a).

General equilibrium effects may also be sizable. In addition to its use in home heating

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[1] The major shale plays in natural gas production are: the Marcellus (mainly in Pennsylvania, about 16 billion cubic feet (Bcf) per day), the Eagle Ford (in Texas, about 6.9 Bcf/day), the Haynesville (straddling Texas and Louisiana, about 6.75 Bcf/day), the Permian (in Texas, about 5.75 Bcf/day), and the Niobrara (in Colorado and Wyoming, about 4.6 Bcf/day).

[2] The drop in production from the Haynesville play is likely because this play is mostly "dry gas" – methane – as the play contains little of the "natural gas liquids," such as ethane, propane, or butane (see 2013. Haynesville continues decline as operators seek out wet gas plays. *Unconventional Oil and Gas Resources*, Dec. 13). Furthermore, the formation is also deeper and more costly to develop than other major U.S. shale formations (Smith 2014).

[3] These data are available at the U.S. Energy Information Agency (EIA) under "Drilling Productivity Report," http://www.eia.gov/petroleum/drilling/.

and electricity generation, an important use of natural gas is as an input into various production processes – for example, the petrochemical industry (U.S. Energy Information Administration 2011, 2014a). As an example, natural gas production will increase fertilizer production, since gas is the primary feedstock for this process. All else equal, this increase will lower the price of fertilizer, which will have beneficial effects on agricultural production, lowering costs and prices. There is also a nascent move to use liquefied natural gas instead of diesel for fueling railway locomotives (U.S. Energy Information Administration 2014a). We do not attempt to assess the potential magnitude of such effects in this paper.

To quantify the increased consumer surplus from expanded natural gas supply, one needs a sense of the price elasticity of demand. There are relatively few studies articulating this elasticity, and the general consensus seems to be that price elasticity has changed over time. For example, Krichene (2002) finds that elasticities based on data between 1918 and 1973 differ fairly sharply from elasticities based on data between 1973 and 1999, with price elasticity of demand lower in the latter years; indeed, the elasticities she estimates for the latter years are statistically indistinguishable from zero. Using more recent data, Arora (2014) finds much larger elasticities. Using weekly data for the period 2008 to 2013, he estimates elasticities in the range of -0.5 in the short run and -0.7 in the long run.[4]

Assuming a price elasticity of demand equal to -0.5, an increase in U.S. natural gas supply of x% would raise consumer surplus by $2p_0q_0x/(1+x)$, where p_0 is the original price and q_0 is the original quantity.[5] In the period from January 2007 to January 2014, U.S. supply increased roughly 26%; as we noted above, this extra output is largely the result of the widespread adoption of fracking. The spot price for the month of January 2007 was roughly $6.39 per thousand cubic feet (Mcf), with traded volume of 1.65 Billion Mcf during the month.[6] Accordingly, a back-of-the-envelope estimate of the increase in consumer surplus when comparing the month of January 2007 and the month of January 2014, assuming all of the extra natural gas output resulted from fracking, is on the order of $4.36 billion, or an increase of $51.9 million each month, on

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[4] Arora's interpretation of "short run" is one month, which coincides with the data we use in our back-of-the-envelope calculations below.

[5] With a constant elasticity of demand equal to -0.5, inverse demand is $p = \left(\frac{A}{q}\right)^2$, where A is a proportionality factor dictated by the data. An x% increase in output from q_0 raises output to $(1+x)q_0$; this in turn increases the area under demand by the amount $\int_{q0}^{(1+x)\,q0} \left(\frac{A}{q}\right)^2 dq$ = $p_0q_0x/(1+x)$. The increase in consumer surplus equals this amount, less the difference in expenditures; a little algebra confirms that the difference in expenditures is $-p_0q_0x/(1+x)$. Thus, the increase in consumer surplus is $2p_0q_0x/(1+x)$.

[6] These data are available at the EIA website. Data on monthly production levels can be accessed at http://www.eia.gov/dnav/ng/hist/n9050us2m.htm, while data on spot prices at the Henry Hub--the benchmark trading price--can be accessed at http://www.eia.gov/dnav/ng/hist/rngwhhdm.htm. Monthly prices are quoted in U.S. dollars per million Btus; .1025 Million Btu correspond to 1 Mcf.

average, if we assume a constant monthly increase in consumer surplus between these two periods.

2.1.2 Benefits to producers

In addition to benefiting consumers, the widespread adoption of fracking has generated gains to producers. One way to measure these gains is via the value of reserves. The conventional logic in non-renewable resource economics is that the value of reserve holdings is the product of reserves and the market price.[7] Between 2007 and 2012, U.S. natural gas reserves increased by about 30%, from about 248 Tcf to about 323 Tcf.[8] Using a base price of $6.39 per Mcf, as discussed above, the value of reserves has increased by about $475 trillion.

Another way to measure benefits to producers is in terms of producer surplus. The increase in recoverable reserves described above shifts the supply curve out, increasing producer surplus. Arora (2014) calculates short-run supply elasticities in the range of 0.1 based on data from 2008 to 2013; long-run elasticities in the range of 0.4. He also notes these values are somewhat larger than estimates based on earlier data, suggesting that the supply based on shale production is more elastic than conventional sources. Assuming a price elasticity of supply equal to 0.1, producer surplus is 10/11 of total revenues.[9] Accordingly, an increase in U.S. natural gas supply of x% would raise producer surplus by 10x/11%, of the original level of producer surplus. As we noted above, U.S. supply increased roughly 26% between January 2007 and January 2014, mainly as a result of the widespread adoption of fracking; the spot price for the month of January 2007 was roughly $6.39 per thousand cubic feet (Mcf), and the quantity traded was 1.65 Billion Mcf. Accordingly, a back-of-the-envelope estimate of the increase in producer surplus when comparing the month of January 2007 with the month of January 2014, assuming the increase in natural gas produced resulted from fracking, is on the order of $9.60 billion.[10]

Of course, to access these new reserves, substantial infrastructure must be put in

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[7] This is often referred to as the "Hotelling valuation principle." A more accurate variation on this theme would net out extraction costs, so the number we present here may overestimate the value of expanded reserves.

[8] These data are also available at the EIA website, at http://www.eia.gov/dnav/ng/NG_ENR_SUM_DCU_NUS_A.htm.

[9] With a constant elasticity of supply equal to 0.1, then $P = (Q/B)^{10}$, where B is a proportionality factor dictated by the data. Producer surplus is $PQ - \int_0^Q \left(\frac{q}{B}\right)^{10} dq = PQ(1 - \frac{1}{11})$.

[10] Of course, there were important changes in demand during this time frame; in particular, natural gas plays a more important role in generating electricity than was the case in 2007. But electricity usage is much less important than home heating in January, and so the electricity issue is less of a concern than is weather. A thorough analysis of the role played by expanding supply upon producer surplus would need to disentangle these various effects; as our point is to offer a rough estimate of the general magnitude of impacts on producers, we leave such an investigation for future work.

place, including new wells, processing units and pipeline delivery systems. An important consideration here is that motivations to expand pipeline systems are not perfectly aligned with social incentives (Oliver et al. 2015). Pipeline tariffs are regulated, which shields pipeline owners from market signals. One implication is that pipeline expansion may occur more slowly than is socially desirable and pipelines can become congested. An important consequence of this congestion is that wellhead prices can be substantially lower than prices at the point of delivery (Oliver et al. 2014). This phenomenon appears to have applied to recent trading activity for natural gas production from the Marcellus play; for example, the natural gas price at Dominion South in October 2014 was 40% lower than at Henry Hub, about twice the typical difference before 2012 (U.S. Energy Information Administration 2014b).

2.1.3 Local and regional economic effects

A substantial literature examines resource-rich economies (Van der Ploeg 2011). On the one hand, a resource boom can result in increased investment in the non-extraction sectors (i.e., an agglomeration economy). On the other hand, a resource boom can increase all local prices, contracting the tradable, non-resource sectors. If the tradable sector has a higher long-run growth potential than the resource sector, then this can ultimately lead to lower growth (“Dutch disease”). Empirical research has found evidence of both positive and negative impacts from oil and gas booms. Given the short history of shale gas development, we first turn to research on conventional oil and gas development to gain insights into potential long-run effects. Jacobsen and Parker (forthcoming) find that U.S. counties that experienced an oil and gas boom in the 1970s and 1980s were worse off in the post-bust (in terms of unemployment and per capita incomes) than they would have been had the boom never occurred. They hesitate to conclude that the boom was a curse, however, because the net present value of the boom and the bust years together is positive.

Marchand (2012), examining three decades of data on employment and earnings in Western Canada under two booms and one bust, does not find a significant change in employment in the bust years. Allcott & Keniston (2014) also use historical data to examine growth and wages at manufacturing firms in counties with and without oil and gas production. Contrary to a Dutch disease, they find that manufacturing growth is higher in resource-abundant counties, implying agglomeration is a more important factor. In a study consistent with the Dutch disease, Michaels (2010) finds that oil-abundant counties in the southern U.S. have smaller manufacturing sectors in terms of *employment share*. However, offsetting the Dutch disease, these counties also attracted more population, resulting in the *absolute size* of their manufacturing sectors remaining the same. In the Brazilian context, Caselli & Michaels (2013) show that oil-rich municipalities report higher spending on public goods and services, however survey and administrative data do not confirm this. A resource curse (Sachs and Warner, 1995), could develop if, for example by proceeds are targeted to wasteful activities, or that institutions will develop that compete for the rents, but offer no clear economic benefits in their own right, and is most likely to apply in economies with weak property rights, for example because of poor legal institutions (Brunnschweiler and Bulte 2008).

Two recent papers examine shale oil and gas specifically, and also do not find evidence of a Dutch disease. Maniloff & Mastromonaco (2014) find higher job growth in counties with tight oil and shale gas wells without affecting wages and employment in tradable sectors. Similarly, Fetzer (2014) using the location of shale formations to instrument for unconventional oil and gas wells does not find a Dutch disease in the tradable sector, though the non-tradable sector does contract.

The expansion of recoverable reserves with hydraulic fracturing offers the potential for large increases in employment. In North Dakota, for example, when the application of fracking techniques opened up the Bakken oil play, significant increases in employment ensued. Figure 2 illustrates: over the period from 2005 to 2014, steady increases in employment in North Dakota correspond to increases in oil production.[11] While this example relates to tight oil production, as opposed to shale gas production (both of which use fracking), the general point is relevant to both. The advantage of using North Dakota to illustrate the point is that prior to the broad adoption of fracking, the state had a relatively small economy with very little non-farm employment. As such, the impacts associated with fracking are much easier to identify without statistical analysis.

Without testing for evidence of the Dutch disease, Weber (2012) finds that employment and income in counties in three Western states increased with natural gas production (with each million dollars in gas production, 2.35 jobs were created in the county of production). A more recent, comprehensive study examines employment impacts of new oil and gas development in all U.S. counties (minus 63 with exceptionally low employment) between 2005 and 2012 (Feyrer et al. 2014). The authors conclude that each million dollars of oil and gas extracted created 0.53 jobs within the county during this period, and an additional 2.4 jobs in counties within 100 miles of new production. Their results suggest the shale boom is responsible for an increase in U.S. national employment during the Great Recession of about 0.4% (Feyrer et al. 2014).

Local and regional economic impacts also include those associated with royalty payments to landowners (where they own subsurface mineral rights), as well as public

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[11] Employment data are from the Bureau of Labor Statistics ("State Occupational Employment and Wage Estimates," http://www.bls.gov/oes/current/oes_nd.htm) and oil production data are from EIA ("North Dakota Field Production of Crude Oil," http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MCRFPND1&f=M).

revenues from taxation, impact fees, permitting, and other activities. Regarding royalty payments, Fitzgerald and Rucker (2014) note that roughly 70% of production is on private lands. They estimate royalty payments for natural gas production from these lands as slightly less than .1% of U.S. national income. For some states, however, these royalty payments are closer to .5% of state income.[12] Feyrer et al. (2014) estimate royalty payments exceeding $150,000 per million dollars of oil and gas produced, within the producing county and nearby counties within a 100-mile radius.[13]

Summary information on increases in state and local public revenues from shale development is sparse. While potentially significant, these revenues are likely to be small relative to the other national and local/regional economic benefits discussed above. Nonetheless, a recent study suggests that local public revenues associated with the shale development boom vary significantly across states, and range from 1 to 10%of total production value (Raimi & Newell 2014). These revenue flows include severance taxes and impact fees, local property taxes on oil and gas, and lease payments for operations on state and federal land. The economic impact of these revenues depends on the uses to which they are put.

2.2 Positive externalities

In addition to the direct market impacts discussed above, the development of U.S. shale gas resources may also generate significant positive externalities. The source of these positive externalities is the lower price of natural gas (relative to other fuels) from increased supply, which drives substitution from coal to gas in electricity generation, and to a lesser extent, from oil to natural gas in the transportation sector. Gas is cleaner than coal or oil upon combustion, generating lower carbon emissions per unit of energy produced (with implications for climate change mitigation), as well as lower emissions of local air pollutants such as fine particulate matter and mercury, with demonstrated human health impacts. Abundant U.S. natural gas supply may also reduce “national security externalities” associated with oil and gas imports. We discuss each of these potential positive external benefits in separate sections below.

2.2.1 Climate change benefits from reductions in CO2 emissions

The potential climate change benefits associated with abundant shale gas depend

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[12] In Texas, Fitzgerald and Rucker (2014) estimate these private royalties are about 0.4% of state income; for Louisiana and Oklahoma, these estimated royalty payments are about 0.65% of state income. For each of these three states, private revenues represent over 75% of statewide natural gas revenues.

[13] Information on royalty rates and land use payments are typically only available in difficult-to-read PDFs. Therefore, there is little research on individual lease negotiations; a notable exception is Vissing and Timmins (2014).

directly on: (1) the degree to which firms and consumers substitute natural gas for more carbon-intensive fuels, such as coal; (2) the net lifecycle GHG effect of substituting gas for other fuels, which must include methane emissions in the natural gas supply chain; (3) increases in energy demand resulting from lower gas prices; and (4) what one assumes about baseline federal (and state) climate policy. Effect (1) will generate clear climate benefits. Additional changes from (2) and (3) will at least partially cancel out those benefits. Even if one were to accurately estimate these three behavioral impacts of abundant shale gas, the magnitude of the causal effect attributable to the "shale revolution" would depend on how much GHG emissions might have been reduced in its absence by climate policy levers.[14]

Brown & Krupnick (2010) simulate the likely impacts of low gas prices on CO2 emissions (but not methane), accounting for increases in demand, under various climate policy scenarios. They find that U.S. CO2 emissions with abundant shale gas drop slightly (less than 1%) through 2030, with the small effect attributable to demand increases, as well as some substitution over time away from renewables. Much more significant drops in CO2 emissions are estimated for abundant-gas scenarios with a federal CO2 cap-and-trade policy (similar to that proposed in the H.R. 2454, Waxman-Markey, in 2009), which reduces both demand increases and substitution of gas for renewables (Brown & Krupnick 2010). Similar electricity demand and fuel-substitution effects (including crowding-out of renewables) is projected in Krupnick et al. (2013b); this analysis predicts a 6.6% drop in CO2 emissions from U.S. electricity generation by 2035, relative to business-as-usual without abundant cheap gas.[15] Other studies have also used computational models of the electricity sector (or the entire economy) under different scenarios of natural gas supply (Burtraw et al. 2012, Venkatesh et al. 2012).

There is also empirical evidence emerging indicating that recent, low gas prices have resulted in the substitution of natural gas for coal as an input in the electricity sector. This fuel switching has resulted in lower CO2 emissions from the electricity sector (Cullen & Mansur 2013; Holladay & LaRiviere 2014; Linn et al. 2014b; Fell & Kaffine 2014; Knittel et al. 2014). These studies focus on the short-run impacts of low natural gas prices, however there are also long-run implications from the retirement of coal-fired generation; roughly 10% U.S. coal-fired generation capacity is scheduled to retire by 2016 (Krupnick et al. 2013b).

While U.S. CO2 emissions from the electricity sector have decreased due to shale gas,

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[14] Recent, relevant policy levers include the Clean Air Act (Linn et al. 2014a) or the Cross State Air Pollution Rule or the Mercury and Air Toxics Standards (Burtraw et al. 2012).

[15] The transportation sector may see a much smaller impact on fuel substitution and overall demand, since gas currently comprises a much smaller share of the fuel mix in this sector, and infrastructure is currently insufficient to support a large expansion in gas-fueled vehicles (Krupnick et al. 2013b).

it is important to consider a couple of other factors. First, the displaced coal could be exported and used elsewhere, which would have global GHG implications (the U.S. exports coal to Europe, and there are contentious proposals to build new export terminals to Asia). Second, apart from increased natural gas supplies, previously un-economic oil supplies have been unlocked by modern hydraulic fracturing and horizontal drilling. As we write this in 2014, the increased oil supply appears to have contributed to a reduction in global oil prices, which may increase demand in transportation and other sectors, with negative implications for climate.

Adding methane into this picture is made more difficult by an ongoing academic debate over the magnitude of methane emissions in the natural gas supply chain. Methane is a potent GHG, with a short-run (100-year) global warming potential about 21-23 times higher than CO2 (Ding et al. 2001). While the peer-reviewed literature contains many estimates, the most recent estimates using two “bookend” approaches--one that estimates atmospheric emissions from aircraft and tall towers (“top-down”), and one that estimates emissions near ground level (“bottom up”)--diverge quite significantly. The reference bottom-up study suggests methane leakage equivalent to 0.42% of gross gas production (Allen et al. 2013), lower than EPA’s estimate (U.S. Environmental Protection Agency 2014a), while the reference top-down study suggests leakage several times greater than that in the EPA emissions inventory (Miller et al. 2013). This debate is critical in understanding the total economic impacts of abundant shale gas, because climate benefits (or damages) hinge directly on the tradeoff of less carbon in consumption, for more methane in production.

Most life-cycle assessments estimate net climate benefits from coal-to-gas substitution in the electricity sector that are robust to the range of methane emissions estimates, though their magnitude, of course, varies depending on those estimates (Brandt et al. 2014).[16] Within the range of available methane leakage estimates, however, substitution for gasoline and diesel in transportation could cause either net climate benefits or net damages (Brandt et al. 2014).

What about the influence of low prices on demand? There is substantial anecdotal evidence of a U.S. manufacturing “renaissance” due to abundant shale gas--in industries in which gas is an important input, such as fertilizers and petrochemicals--with European firms (facing gas prices much higher than U.S. prices) constructing new U.S. facilities, and domestic firms increasing their investments in U.S. facilities (Johnson & Tullo 2013, Northam 2014). Demand responses to lower natural gas prices are

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[16] A Life-cycle assessment calculates the environmental impact from the beginning of a product's life to the end; in the case of shale gas, it would calculate the greenhouse gas emissions associated with producing, processing, transporting, and consuming the natural gas.

augmented by commensurate drops in electricity prices. The electricity price is almost perfectly correlated with natural gas prices (Linn et al. 2014b, show the elasticity of wholesale peak-electricity price with respect to natural gas price is close to one in many parts of the U.S.) However, given relatively low price elasticity of demand for electricity, we would expect relatively small increases in electricity demand from recent electricity price decreases (Krupnick et al. 2013b, Brown & Krupnick 2010).

2.2.2 Local air quality benefits

Apart from potential GHG emissions reductions from switching from coal to natural gas in the electricity sector, there will also be local benefits for individuals living near coal-fired power plants. Coal-fired plants emit more local and regional pollutants (e.g. fine particulate matter, mercury, sulfur dioxide) than natural gas-fired plants, so one would expect to see health impacts on people downstream of coal-powered plants. Research is underway to examine these connections (LaRiviere et al. 2014).

2.3 Decreased vulnerability to supply disruptions

Rising natural gas prices at the beginning of the last decade supported the common presumption that in order to meet future demand, the U.S. would need a new pipeline to augment supplies from Alaska, and that it would increasingly rely on imports from Canada and liquid natural gas (LNG) imports from potentially less friendly trading partners such as Russia (Joskow 2013, Deutch 2011). This view prevailed in government reports through the mid 2000s (U.S. Energy Information Administration 2007) until technological advances brought in a flood of new production from shale formations.

Periods of high oil prices have drawn the attention of economists to potential “national security externalities” associated with oil imports--or, more precisely, the increased vulnerability to supply disruptions from unstable trading partners--which have some relevance to natural gas markets. As Metcalf (2014) carefully points out, these impacts are not really externalities, though a reduction in supply vulnerability due to an expanded domestic resource base could certainly have positive impacts on the U.S. economy. Lower imports may reduce rents paid to foreign oil producers during disruptions (with positive distributional impacts for the U.S.), reduce GDP losses from disruptions, and reduce defense expenditures related to increasing the stability of foreign supply (Brown & Huntington 2013). For example, the magnitude of the first two effects (rents to foreign producers and GDP losses) may imply a “security premium” for imported over domestic oil in the U.S. on the order of $2.00 per barrel, a premium that can be expected to rise moderately over time with both GDP and oil prices (Brown & Huntington 2013). Europe depends heavily on Russian natural gas, and over the past two decades there have been supply disruptions and price increases consistent with political motivations (Stegen 2011). Given current events in Russia and Ukraine, domestic shale gas production as well as LNG imports from the U.S. may also have important energy security implications for Europe.

All other estimates of U.S. national security premiums in the literature (Brown & Huntington 2013, Bohi & Toman 1993, Leiby 2007) have to do with the benefits of reducing foreign *oil* imports, primarily from the Middle East. As noted earlier, fracking has also unlocked significant U.S. tight oil resources. The impacts of this on world oil prices and the influence of OPEC are already being described in the media (see: Krauss, C. 2014. OPEC split as oil prices fall sharply. *New York Times*, 13 October), though not, as yet, in the academic literature.

Existing estimates cannot be directly transferred to the context of natural gas imports, given the important differences in trading partners and the scale of U.S. imports. However, if abundant shale gas causes significant U.S. substitution of gas for oil, these estimates from the literature on oil imports will represent potential additional economic benefits from abundant gas. The degree of such substitution will hinge critically on fuel switching in the transportation sector, the destination of most U.S. oil imports. This is a fact that appears to be poorly understood in political discourse regarding national security implications of shale gas.

3.0 THE COSTS OF SHALE GAS DEVELOPMENT

3.1 Direct market impacts

If abundant shale gas displaces other energy sources in electricity generation, household and industrial use, and transportation, this could cause reductions in consumer and producer surplus in markets for other fuels and energy technologies. For example, renewable energy technologies and carbon capture and storage could be affected in this way (Jacoby et al. 2012). Currently, much of the impact of the shale boom on natural gas prices has been in North America, so some of these negative direct market impacts could be mitigated by trade (e.g., coal exports). Like other impacts in general equilibrium, quantifying the impacts of increased U.S. gas supply and lower gas prices on other energy markets is beyond the scope of this study.

3.2 Negative externalities

Negative externalities have been at the center of most discussions on shale gas development and these concerns have resulted in moratoriums on fracking at the city and town level (e.g., Denton, Texas), at the state level (e.g., New York), and even at the country level (e.g. France). The most often-cited concern is in regards to the impact on water. Other areas of concern have focused on the impacts on wildlife, local air quality, community disruptions, property values, and health. Each of these are discussed below.

Weighing these potential negative impacts against the benefits described in Section 2 would seem to require monetization; in the discussion that follows, we refer to monetized estimates in the literature, where they are available. However, "best practices" in benefit-cost analysis suggest that the analyst should quantify, to the extent possible, physical impacts of a policy or other change, and monetize physical impacts where possible (U.S. Environmental Protection Agency 2014b). But the inability to convert all physical impacts to monetary values is one reason that a strict benefit-cost test is rarely used (or recommended) to make important public decisions (Arrow et al. 1996). Impacts that cannot be monetized, including some of those discussed below, should still be carefully described. Thus, the (primarily) scientific literature discussed here provides information that is strongly relevant to assessing the benefits and costs of shale development, even where it falls short of monetizing impacts.

3.2.1 Water resource impacts

The negative water resource implications of shale gas development have been heavily covered in the popular media.[17] Hydraulic fracturing uses significant water inputs, requires wellbores that traverse drinking-water aquifers, and generates large wastewater streams. Risks to groundwater have gained much the attention in the popular press, however, a survey of industry, academic, NGO, and government experts found that surface water risks may be greater (Krupnick et al. 2013a). Research quantifying the externalities from water withdrawals and wastewater disposal is only beginning to catch up with public interest and concern. Below we discuss evidence of negative externalities to both surface and groundwater resources, divided into subsections based on quantity or quality concerns.

3.2.1.1 Surface water depletion

Water used in hydraulic fracturing could reduce the flow of rivers and streams, diminishing ecosystem services and water available for other diverted uses.[18] The

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[17] See, for example: Urbina, Ian. 2011. Drilling down series. *The New York Times*. 23 February – 31 December. Available at http://www.nytimes.com/interactive/us/DRILLING_DOWN_SERIES.html; and Fox, Josh, dir. 2010. *Gasland*. New Video.

[18] Water inputs in hydraulic fracturing vary with geology, the amount of recoverable gas, number and length of horizontal wellbores, and other factors (e.g., wells in the northeastern U.S. require 2 to 4 million gallons of water per well (Veil 2010) and wells in Texas and Oklahoma require 5 million gallons (Nicot et

empirical evidence for negative externalities directly related to freshwater extraction is thin. Along many dimensions, the quantities of surface water used for shale gas development are small. For example, surface water is, on average, a plentiful resource in the northeastern U.S. and withdrawals for shale gas development represent a very small fraction of total withdrawals (Mitchell et al. 2013). Even in Texas where water is more scarce, hydraulic fracturing amounts to less than 1% of statewide water withdrawals (Nicot & Scanlon 2012). And in comparison to the water intensity in producing most other fossil fuels, such as coal, conventional and unconventional oil, shale gas development is less water intensive (Kuwayama et al. 2014).

However, the risks associated with surface water consumption can be expected to vary both over time and space. Little water is required when gas is actually being produced, thus withdrawals in any play, no matter how significant, will be transient. Most of the water consumption in shale gas production occurs within one to five days during the hydraulic fracturing process and if this water was all diverted during a low-flow period (summers, droughts) there may be more significant ecosystem impacts (Entrekin et al. 2011). Furthermore, within a river basin, small streams (and the organisms therein) may be more sensitive to changes streamflow than larger rivers. In addition, the regulation of water withdrawals and water rights structures will mitigate the impacts of withdrawals to varying degrees. Additional research on these spatially and inter-temporally variable impacts is warranted.

If the physical impacts of water withdrawals for fracking were quantified, they could also be monetized. Estimating the value of instream water for recreational use or ecosystem maintenance often requires nonmarket methods such as recreational demand models, contingent valuation (CV), and hedonic housing models. A substantial literature using these methods now quantifies the marginal value of surface water left instream for recreation, riparian and wetlands restoration, and other purposes in many different parts of the world. Most of these focus on arid regions, where such values may be reasonably high (Ojeda et al. 2008, Loomis et al. 2000). Spatial and temporal dimensions appear to be particularly important for recreational demand--fishing is a good example (Hansen & Hallam 1991). Individuals may also hold significant value for the maintenance of flow in surface water systems that support endangered species habitat (Loomis 1987). Thus far, there are no estimates in the literature of the economic value of reducing risks of shale gas extraction related to surface water scarcity.

3.2.1.2 Surface water pollution

In contrast to surface water withdrawal impacts, emerging evidence suggests that surface water quality impacts from shale gas development may be significant.

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al. 2014)).

Important impacts thus far have to do with the release of partially-treated wastewater to rivers and streams. After a well is fracked, varying amounts of the fracking fluids injected into the well returns to the surface (as “flowback”) alongside water that was present in the shale formation (“produced water”). This wastewater stream contains naturally occurring salts, heavy metals and radioactive material. It can be recycled to frack additional wells, trucked to industrial wastewater treatment facilities, or transported to deep injection wells (Jiang et al. 2014). In 2011, Pennsylvania banned shipments of shale gas wastewater to municipal sewage treatment plants, though industrial “centralized waste treatment” (CWT) facilities continue to play a significant role in shale gas waste treatment and disposal (Pennsylvania General Code 2010, Zhang et al. 2014). Downstream surface water quality impacts from incomplete wastewater treatment have been demonstrated for chloride (Olmstead et al. 2013), bromide (Wilson & VanBriesen 2013), and radionuclides (Warner et al 2013a, Zhang et al. 2014). These effects may affect the quality of even treated drinking water, as well as important recreational fish species, causing economic damages, but they are specific to areas that send waste to CWTs. Most shale plays send liquid waste to deep injection wells, dramatically reducing these risks.[19]

Some risks to surface water are present regardless of location. First, land clearing and the construction of well pads, pipelines, and roads may increase stormwater runoff, erosion and sedimentation of local rivers and streams. Olmstead et al. (2013) provide empirical evidence of increases in total suspended solids downstream of shale gas well pads in Pennsylvania. Second, the risk of accidental releases contaminating surface water has been a focus of public concern. The only empirical study to examine this possibility shows no statistical evidence of systematic pollution associated with gas wells in Pennsylvania through 2011 (Olmstead et al. 2013). However, individual spills can and do occur (e.g., Papoulias & Velasco 2013).

Like the other negative externalities described in this paper, any monetization of shale gas impacts on water pollution would require the development of an appropriate counterfactual, keeping in mind that water quality impacts from coal mining and other alternative energy development may be equally as, or more, severe (Jenner & Lamarid 2013). To monetize surface water pollution impacts (or the value of their mitigation), benefits transfer could be used, since the literature contains many estimates of the economic value of water quality improvements (Olmstead 2010). Given the impacts discussed above, studies focusing on salinity (Characklis et al. 2005) may be relevant (in watersheds with high background salinity levels), as well as those focusing on suspended solids (Poor et al. 2007).

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[19] Disposal of waste in injection wells poses different risks; the injection of large quantities of fracking waste has caused small earthquakes in states such as Arkansas, Ohio, and Oklahoma (Ellsworth 2013).

In addition, two recent CV studies address the value of reducing general surface water risks from shale gas development. Bernstein et al. (2013) estimate a mean willingness to pay among Pennsylvania residents of $10.46 per month (in aggregate, about $9.3 million per year), for eliminating all risks to area waterways through the safety measures, such as containment ditches, around gas wells. Siikamäki & Krupnick (2014) find that Texas households would be willing to pay about $24 per year to eliminate pollution related to shale gas development in 1% of the state's surface water bodies and Pennsylvania households would be willing to pay about $10 per year.

3.2.1.3 Groundwater depletion

While the amount of groundwater used for fracking in the humid eastern U.S. is negligible, groundwater aquifers have been a significant source of water for fracking in arid and semiarid regions (Nicot et al. 2014). However, even in semi-arid states, groundwater withdrawals for fracking represent a small fraction of total statewide withdrawals (Murray 2013, Nicot and Scanlon 2012). The extent to which the resulting groundwater depletion represents a negative externality depends on geologic as well as economic factors.

Some aquifers are essentially non-renewable resources, thus the efficient price of groundwater supplies would include Hotelling rents, accounting for the fact that using up nonrenewable water today leaves less for tomorrow. An example is the Trinity aquifer, the primary source of groundwater for energy development in the Barnett Shale, and a major municipal water source experiencing significant depletion (Nicot et al. 2014). Groundwater in Texas is private property governed by the rule of capture, thus market exchanges between landowners and energy could, in theory, incorporate this intertemporal externality. Spatial externalities, however, such as the impact of aquifer depletion for energy development on municipal water availability and cost, may be difficult to address through markets in this setting (Provencher & Burt 1993, Hanak 2005).

If accurate estimates of groundwater depletion for hydraulic fracturing could be developed, a reasonable approach to valuing the potential value of marginal damages from this depletion would be to consider the opportunity cost. For example, the marginal value of water inputs to lost agricultural production, among uncompensated agriculture users of a common aquifer, would be relevant in some regions. In others, the relevant marginal damages might be to urban users. Cutter (2007) estimates the marginal damage associated with reduced ability to withstand drought in groundwater-dependent urban areas; aquifer depletion in this study resulted from increased impervious surface due to urban land development, but the technique could be adapted to value the damages associated with competition from fracking for shared groundwater.

3.2.1.4 Groundwater pollution

The academic literature has focused on the potential for groundwater contamination from either leaking well casings, or seepage from surface storage pits (Osborn et al. 2011, Warner et al. 2013b). Regions with plentiful methane and brine in the sub-surface often have high groundwater levels of these constituents, thus determining the causal effect of energy development on groundwater quality can be difficult. Furthermore, public records of complaints of groundwater contamination are incomplete given nondisclosure clauses in settlements (Gamper-Rabindran 2014). Results from studies observing methane in water wells near shale gas development in the Marcellus and Barnett shale plays are consistent with well casing and cementing failures (Darrah et al. 2014). On the other hand, public attention has focused on the potential for groundwater contamination from the hydraulic fracturing of the shale rock. The potential for the movement of fracking fluids from deep shale formations to overlying aquifers through natural or induced fractures is actually quite low (Vengosh et al. 2014).

The literature contains several estimates of the benefits of groundwater protection (or damages from contamination) in contexts outside of shale gas development (Boyle et al. 1994, Sun et al. 1992, Abdalla et al. 1992) that could be used in a cost-benefit analysis. Some of these studies focus on the cost of averting expenditures (e.g., the purchase of bottled water) by affected households, which is possible as at least a short-term solution.

Two recent studies focus on the economic value of groundwater contamination from fracking, itself. First, in a stated-preference study, Siikamäki & Krupnick (2014) estimate households' willingness to pay, in Pennsylvania and Texas, for reducing the risk of groundwater contamination. They estimate average household willingness to pay of \$33 per year to reduce by 1,000 the number of groundwater wells with potential pollution problem. Second, in a revealed-preference study, Muehlenbachs et al. (2014) estimate the willingness to pay to avoid the risks to groundwater contamination using transaction records of properties in proximity to shale gas wells with and without access to piped water. Groundwater-dependent homes within 1.5km of shale gas wells lose about 3.4% of their market value after a well is drilled, whereas properties with access to piped water from public water sources, conversely, experience small net gains (6.6%), likely because royalty payments made to homeowners for the mineral rights offset other costs of proximity (such as impaired views or traffic congestion). The difference between the change in price for the properties with and without access to piped water provides an estimate of the potential groundwater contamination (i.e., the estimates above imply groundwater concerns reduce property values by 10%). Therefore, regardless of whether the risk to groundwater is real or only perceived, the market has reacted and there have already been large impacts on local property values.

3.2.2 Habitat fragmentation

Compared to impacts on water resources, the impact of shale gas development on wildlife has garnered less attention in the popular press and academic literature. Forest fragmentation from the construction of roads, pipelines, and well pads in Pennsylvania has been documented (Drohan 2012) and there is an extensive literature on the effects of habitat fragmentation on biodiversity (Fahrig 2003) implying that shale gas development would also have impacts on biodiversity. Loss of migratory routes, increased predation, and increased illegal hunting are suggested as the primary pathways that shale gas might impact wildlife (for a review of literature on the impacts of unconventional energy development on wildlife see Northrup and Wittemyer 2013).

On a positive note, with the advent of horizontal drilling, multiple wellbores can be drilled from the same well pad, resulting in less forest fragmentation than would be the case with spatially diffuse vertical wellbores. However, nonetheless, multi-well pads cover larger areas than vertical wellbores, and the surrounding land is typically not reclaimed, even after fracking equipment has been removed.[20] Allowing the option to postpone reclamation becomes important in regards to the future liability of land reclamation. Bonds to ensure reclamation are arguably too low and legacy issues arise when firms can continuously postpone cleanup (Muehlenbachs, Forthcoming). An important research agenda is therefore the optimal siting of shale gas infrastructure as well as the interaction between development and species preservation, including the use of habitat offset programs (Doherty et al. 2010) and agglomeration bonuses (Parkhurst et al. 2002).

3.2.3 Local air quality impacts

Local emissions from shale gas activities might arise from diesel and road dust from transporting equipment and water; diesel combustion from drilling and hydraulic fracturing at the well; fugitive emissions from the well; or combustion at compressor stations. Pollutants can include volatile organic compounds, VOCs, nitrogen oxides, NOx, particulate matter, and PM (with VOCs and NOx as ozone precursors) (Kemball-Cook 2010; McKenzie et al. 2014; Gilman et al 2013; Helmig et al. 2014; Litovitz et al. 2014). Estimates of the quantity of these emissions in Pennsylvania in 2011 suggest they were only a small fraction of total statewide emissions in the state (Litovitz et al. 2013).

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[20] This is so that operators have the option to come back and drill more wellbores on the same well pad in the future.

3.2.4 Local boomtown disamenities

Temporary boomtowns have been the subject of research in a long history of sociology papers (see Smith et al. 2001 for a review) and to date, shale-induced boomtowns are mainly being researched in sociology, largely focused on local residents' perceptions (e.g., Theodori 2009; Brasier et al. 2011). With a boomtown comes an influx of new migrants, putting pressure on pre-existing infrastructure. Increased traffic congestion is one example, but heavier traffic on existing roads may cause other problems, as well. For example, increases in heavy truck traffic, transporting water to and from well pads, poses a risk to other motor vehicles on the road; traffic accident rates are higher in counties with more shale gas development (Jove et al., forthcoming).

Newspaper articles describing increased crime rates, sexually transmitted diseases, and substance abuse in shale-boomtowns abound.[21] Preliminary statistical evidence suggests increased crime in shale-rich counties in recent years (James & Smith 2014). In contrast, Feyrer et al. (2014) find no consistent patterns regarding aggregate crime in producing counties; some individual types of crime may have increased in some counties, but the analysis cannot reject relatively small (or no) increases, even for the highest-producing counties. While crime is often discussed as a potential negative externality associated with shale development, we should note that as in intentional act, it may not properly be classified as such (Baumol and Oates 1988).

3.2.5 Aggregate measures of external damages

Health literature, unrelated to shale gas, has demonstrated that the air and water pollutants discussed in earlier parts of this section adversely affect human health. However there is little research demonstrating an impact from shale gas development on human health. Notable exceptions lie in the literature on birth outcomes. Examining data on over 120,000 births between 1996 and 2009 in rural Colorado, McKenzie et al. (2014) find an association between proximity to natural gas wells and birth defects (congenital heart defects and neural tube defects). They find a small negative association with low birth weight and premature birth. Hill (2012, 2013) uses a unique identification strategy for a causal estimate of infant health; she examines mothers in proximity to permitted, but yet-to-be-drilled wells as a control group, as these mothers should be similar in unobservable characteristics to mothers near drilled wells. Hill (2012) finds that in Pennsylvania exposure to a shale gas well within 2.5 km of a mother's residence results in decreased average birth weight. Hill (2013) finds that in Colorado exposure to a shale gas well reduces birth weight and gestation length. The

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[21] For example, "As Oil Floods Plains Towns, Crime Pours In," Jack Healy, *New York Times*, November 30, 2013, or "Dark side of the boom," Sari Horwitz, *Washington Post*, September 28, 2014.

pathways for these effects are not specified in the empirical analyses.

A burgeoning literature quantifies the impacts of shale gas development on property values, which can incorporate a wide range of amenities and disamenities. Using data on property transactions Gopalakrishnan & Klaiber (2012) and James & James (2014) find that proximity to a shale gas well reduces property values. Delgado et al. (2014) also find weak evidence of this, and Muehlenbachs et al. (2014) find this to be the case for properties that use private groundwater wells. At a broader level, both positive and negative impacts have been found; Weber et al. (2014) find Texas property values are higher in zip codes with shale, hypothesized to be driven by local public finances. Boslett et al. (2014) find that properties in New York would have gained value had New York not imposed a moratorium on hydraulic fracturing. To the extent that booms and busts are capitalized into the housing market, we have some evidence of the boom being short lived. Muehlenbachs et al. (2014) find that there are increases in property values when shale gas wells are drilled in the general vicinity of a property (i.e., within 20km), however this is only in the first year that wells are drilled. Furthermore, wells that were permitted but have remained undrilled have a negative impact, which increases with the length of time since permitting.

4.0 CONCLUSIONS

The widespread adoption of hydraulic fracturing, or fracking, has had profound impacts at the national, state and local levels. The impressive increase in economically viable reserves has led to lower natural gas prices, and broader penetration of natural gas into electricity generation and industrial use. At the most basic level, increases in equilibrium quantities and decreases in price expand consumer and producer surplus, as well as the value of reserves. Increased use of gas in electricity generation has facilitated a reduction in the use of coal, with attendant air quality benefits (likely for GHGs, and almost certainly for local air pollutants). To some extent, abundant shale gas (and tight oil) may also reduce national security externalities from fossil fuel imports. Short-run increases in employment and regional economic activity have provided welcome relief from the Great Recession in producing regions. All these elements represent societal gains, and while we cannot estimate the sum of these gains, it has undoubtedly been very large. A back-of-the envelope estimate of gains in consumer surplus, alone, when comparing the months of January 2007 and January 2014, is $4.36 billion; producers have seen the value of reserves skyrocket, and have enjoyed increases in producer surplus, as well.

Negative externalities have also been identified. The possibility of a resource curse, while unlikely in the U.S. context, may be relevant elsewhere. Empirically demonstrated water resource impacts include pollution from the release of partially treated shale gas wastewater to rivers and streams, which has affected downstream drinking water and ambient water quality; erosion and sedimentation in rivers and streams from shale gas infrastructure; and migration of methane to local drinking water wells, likely from faulty gas well casing and cementing. While there is a literature on water quality valuation, estimates specific to shale gas are small in number and hard to generalize. Similarly, impacts on habitat fragmentation, local air quality, and boomtown disamenities such as crime and traffic congestion are still only sparsely quantified, and have yet to be monetized.

Despite the paucity of data on the physical and economic magnitudes of negative externalities, it is possible to draw some important conclusions from our review. First, none of these externalities are priced, so even without estimates of their magnitude, the social costs associated with fracking are likely larger than the private costs. Second, despite the presence of negative externalities, the magnitude of benefits described above suggests a very high “burden of proof” for those who would support forgoing, or very significantly constraining, shale gas production on economic grounds. Third, fracking’s unpriced social costs are mainly local in nature, while its benefits are local, national, and global. This distinction implies the phenomenon has a transboundary flavor, though in terms of benefits, as opposed to the more thoroughly studied problem of transboundary negative externalities.

While we have focused our attention on natural gas production, fracking has also dramatically expanded U.S. oil production. This latter application has similar benefits and costs to those we have explored for natural gas, but some important differences. Note, for example, that any anticipated climate-related benefits from abundant shale gas may be counterbalanced by abundant tight oil (for example, in terms of emissions from the transportation sector). Similarly, the debate regarding how best to transport these oil resources, which have overwhelmed the U.S. pipeline system, must include the elevated risk of rail disasters, as well as delayed rail transport for other sectors (such as forestry and agriculture).

Thus, the economic research boom that has accompanied the shale revolution may stretch to the far horizon. Productive contributions by economists may be made in identifying the “big ticket” negative externalities, and proposing cost-effective policies for addressing these risks. Instructive new research might also estimate benefits and costs of local and state-level fracking moratoria, and describe the distribution of benefits and costs from such policies, so as to make the resulting tradeoffs more transparent, and thus more salient.

ACKNOWLEDGMENTS

We thank Naima Farah and Xiaoli Zheng for research assistance.

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Figure 1. Natural gas production from major U.S. shale plays, 2007-2014

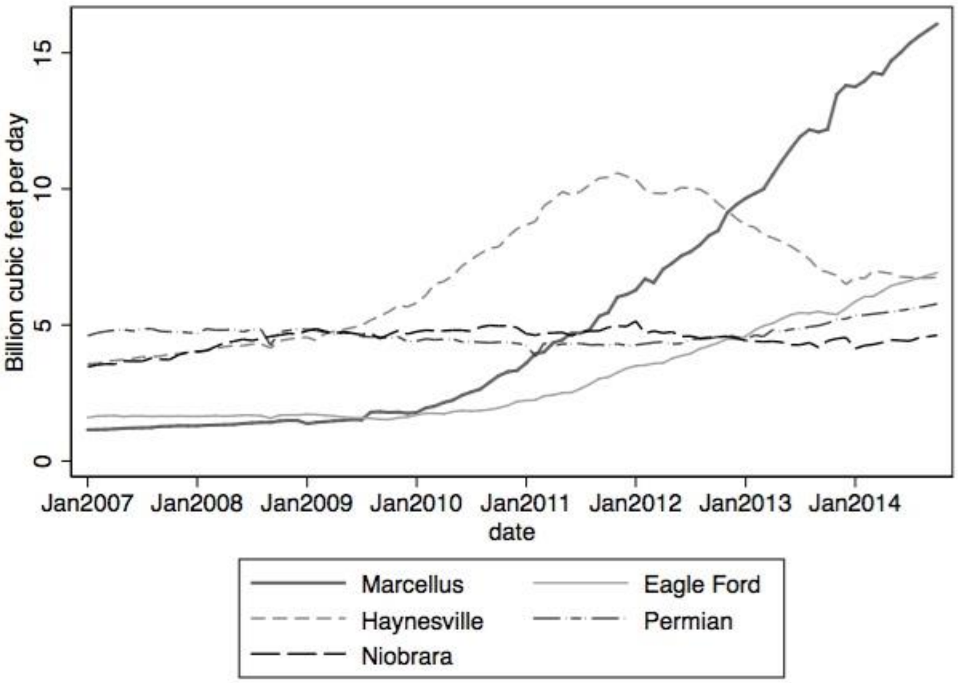
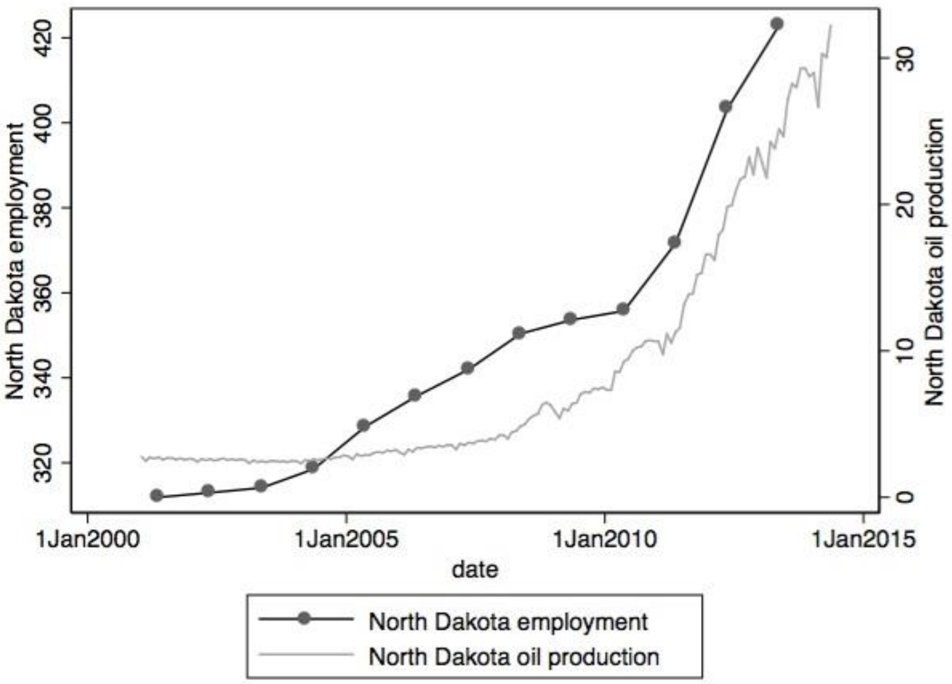


Figure 2. Employment and oil production in North Dakota, 2000-2014



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