Is Abundant Natural Gas a Bridge to a Low-carbon Future or a Dead-end?

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December 15, 2018

Abstract

A fierce debate rages on whether abundant natural gas is a bridge to a low-carbon future or a hindrance to long-term decarbonization. This paper uses a detailed energy-economic market equilibrium model to study the effects of an upper bound case of natural gas availability. We show that a market-driven abundant natural gas supply can provide substantial reductions in air pollution but does not considerably reduce CO_2 emissions in the longer-term, especially relative to a moderate carbon price. However, we quantify large welfare benefits from abundant natural gas. The spatial disaggregation of our results allows for a clear picture of the distributional impacts of abundant natural gas under different carbon price scenarios, illustrating welfare gains by most regions regardless of whether there is carbon pricing, but substantial heterogeneity in the welfare gains.

Keywords: welfare, natural gas revolution, distributional impacts, carbon pricing.

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"[...] natural gas is the Rorschach test of energy policy. [...] it can be either an essential tool for meeting the challenge of climate change or another dirty fossil fuel that will speed the planet down the path to calamitous warming."

— New York Times, December 22, 2014

1 INTRODUCTION

In recent decades, there has been a dramatic boom in natural gas production in the United States, spurred by the hydraulic fracturing ("fracking") technological innovation, which opened up vast shale formations to economic recovery of natural gas (Joskow, 2013; Huntington, 2017). This boom has led to low natural gas prices, fuel switching to natural gas for electricity generation (Newell and Raimi, 2014; Holladay and LaRiviere, 2017; EIA 2018). Fuel switching away from coal (and to a lesser extent oil), can reduce emissions from electricity generation due to lower carbon content of the fuel (Brown et al., 2010; McLeod et al., 2014). Indeed, this fuel-switching is responsible for a sizable fraction of the emissions decline in the United States over the past decade (CEA, 2017). However, many have argued that while a large-scale transition to natural gas may reduce emissions in the short-run, it may actually increase emissions in the long-run by leading to lock-in of a low-cost emitting technology (Shearer et al., 2014; McJeon et al., 2014).

This paper investigates the degree to which natural gas can serve as a "bridge" to a low carbon future by helping or hindering reductions in CO_2 emissions in the coming decades. Our study uses a large-scale energy-economic model of the United States—the National Energy Modeling System (Yale-NEMS)—to assess the extent to which abundant natural gas availability reduces or increases long-run emissions, and welfare, and the effectiveness in reducing emissions relative to a moderate climate policy.[1] While no model is perfect, the NEMS platform is widely accepted as the "gold standard" for prospective energy market analysis (Winebrake and Sakva, 2006). We find that a scenario of truly abundant natural gas does reduce local air pollution and greenhouse gas emissions, while at the same time providing a large welfare benefit. However, the reduction in emissions is modest relative to what a carbon price (e.g., from a carbon tax) set linearly rising to roughly $46 per ton CO_2 in 2040 could achieve. Furthermore, as we approach 2050, emissions under the abundant natural gas scenario are even slightly higher than the reference case due largely to less deployment of renewables. We further examine heterogeneous welfare effects across regions, illustrating that while all regions see welfare gains from abundant natural gas (regardless of whether there is a carbon policy), there is substantial heterogeneity in the welfare effects. Our welfare estimates are subject to the caveat that we cannot quantify all of the potential local impacts of natural gas production and distribution, but illustrative calculations suggest that even if these are included, the welfare benefits would remain large.

This is not the first paper to tackle the policy-relevant question of whether abundant shale gas increases or decreases net emissions. Indeed, there are several modeling analyses of this question that take different approaches (e.g., Brown et al., 2010; McJeon et al., 2014; Holladay and LaRiviere, 2017; Linn and Muehlenbachs, 2018; Johnsen et al., 2018). Our paper is distinctive by focusing on scenarios with abundant natural gas based on optimistic—but realistic—recent regional estimates of U.S. natural gas resources, consistent with an upper bound natural gas production case that may come about due to richer resources than expected in the reference case

[1] Yale-NEMS is just NEMS hosted on a server at Yale, which is based on the EIA's latest archived NEMS code as of June 2017. Yale-NEMS has the same features and produces the same model results as the EIA's version. The version of NEMS used for this analysis corresponds to the data and model code used by EIA for the AEO2017. The published documents for AEO2017 can be referred to: https://www.eia.gov/outlooks/archive/aeo17.

(but within uncertainty bounds) and/or an opening up of federal or state lands to natural gas production. Further, we make several new contributions to the literature.

First, we develop a concise economic theory framework that illustrates how adding natural gas could either increase or decrease emissions and elucidates the theoretical links between the outcomes from the computational model, which distinguishes this work from previous modeling papers on natural gas (e.g., Brown and Krupnick, 2010; Brown et al., 2010; Shearer et al., 2014). The static framework we present also clearly lays out the welfare effects of supply increase in natural gas, identifying the economic forces driving welfare. This short theory section crystallizes the basic insights that we then explore using Yale-NEMS, akin to how the theory framework of Gerarden et al. (2016) laid the groundwork for an analogous energy modeling exercise.

Second, we are not aware of any other study that uses the same modeling platform to tackle our research question from both economic and environmental perspectives. Yale-NEMS is an ideal tool for our analysis because of its granularity and comprehensiveness. It is a detailed regional equilibrium model that covers all major U.S. energy markets and end-use demand sectors. It also enables us to quantitatively analyze the impacts of fundamental and policy alterations on markets, welfare, and the environment relative to the baseline projections based on a comprehensive coverage of existing policy and technology status. This detail has led numerous authors to use the NEMS platform for the analysis of changes in the energy system (e.g., Nogee et al., 2007; Goulder, 2010; Brown et al., 2010; Auffhammer and Sanstad, 2011; Mignone et al., 2017).

Third, we are the first to calculate the welfare effects of abundant natural gas both with and without a carbon policy, including monetized CO_2 and air pollutant impacts. The welfare impacts of the natural gas boom have been of growing interest to economists. Bartik et al. (2016) estimate the local welfare impacts of fracking and conclude that fracking results in substantial oil and gas industry development and growth in the local economy. Hausman and Kellogg (2015) estimate the retrospective consumer and producer surplus effects associated with the recent natural gas supply boom using their own estimated natural gas supply and demand elasticities to find positive gains for consumers but losses for producers. Linn and Muehlenbachs (2018) investigate electricity generation and emissions over the past several years when natural gas prices have been low and econometrically estimate the relationship between fuel switching and electricity prices across regions. Our work differs in quantifying a broader set of welfare effects capturing how multiple inter-related energy markets and sectors respond to changes in market fundamentals and policy, and our modeling includes more detail on emissions than in previous research.

Finally, we examine the winners and losers of an abundant natural gas scenario, accounting for both direct welfare and environmental effects from greenhouse gas emissions and air pollution emissions based on recent air quality modeling work (Muller and Mendelsohn, 2009; Muller et al., 2011; IWG, 2016). We show that the regional impacts from abundant natural gas are quite similar regardless of whether there is a carbon policy or not. In both cases, the region around Texas and the West Coast region benefit the most. But, as mentioned already, nearly all regions benefit from abundant natural gas.

The paper is organized as follows. Section 2 provides the background on the U.S. natural gas market. Section 3 presents the stylized economic model. Section 4 introduces Yale-NEMS and our scenario designs. Section 5 presents our primary quantitative simulation results, while section 6 examines the welfare implications. Section 7 concludes.

2 BRIEF BACKGROUND ON NATURAL GAS IN THE UNITED STATES

Between 2001 and 2016 (the most recent estimate available from EIA), total natural gas production in the United States increased 35% to 27 Tcf (Figure 1). This increase can be attributed to a boom in shale gas production, which exceeded 53% of total production in 2016. Most of this new production is from six major shale plays: Barnett, Eagle Ford, Fayetteville, Haynesville, Marcellus, and Woodford spread in Texas and Pennsylvania (Joskow, 2013; Hausman and Kellogg, 2015; Cooper et al., 2016). As is also seen in Figure 1, the increase in production has been accompanied by a decrease in natural gas prices, with the Henry Hub trading price dropping by 75% between 2008 and 2016, reaching $2.5 per MMBtu (in 2016$).[2]

Lower natural gas prices provide benefits to consumers and firms, with positive direct economic impacts (Mason et al., 2015). As natural gas has a lower carbon intensity than coal and emits fewer air pollutants when combusted, a switch from coal to natural gas for electricity generation can also have direct environmental benefits. Indeed, total U.S. greenhouse gas emissions have been dropping, and this has been determined to be partly attributable to fuel switching from coal to natural gas (CEA, 2017). In April 2015, for the first time ever in the U.S., natural gas replaced coal as the largest fuel source of power generation.[3] At the same time, the increased domestic natural gas production has also changed the U.S. from a natural gas importer to a natural gas exporter (EIA 2017a). As of April 2016, U.S. sent its first liquified natural gas (LNG) cargo to Europe from the Sabine Pass LNG terminal.[4] As production continues growing,

[2] The Henry Hub is a distribution hub located in Erath, Louisiana. Prices traded at Henry Hub are considered to be the base price for the North American natural gas market.

[3] Source: http://www.eia.gov/electricity/data/state.

[4] Source: https://www.maritime-executive.com/article/first-us-lng-cargo-to-europe-reaches-port.

LNG exports from the U.S. are expected to play a pivotal role in the international energy market (IEA 2016).

This paper explores an upper bound estimate of the quantity of low-cost abundant natural gas—a world where some of the most optimistic assumptions on the extension of the 'shale gas revolution' come true. The next section develops a simple theory framework for understanding what abundant low-cost natural gas can mean for emissions and welfare.

3 A THEORETICAL MODEL

To operationalize a world with substantially more abundant natural gas, a natural starting place is to consider a shift in the natural gas supply curve downwards, so that for every level of production of natural gas there is a lower marginal cost. With this as the starting point, we propose a simple static partial equilibrium model with a single output market that utilizes energy inputs. While we recognize that there are dynamics at work—and our NEMS simulation results include these—the purpose of this section is purely to provide some intuition for the economics at work. Our approach to developing a simple theory model is in line with a series of studies focusing on the environmental implications of low-carbon policy instruments and technological advancement (Fischer and Newell, 2008; Holland et al., 2009; Horowitz and Linn, 2015; Gerarden et al., 2016). To keep the section concise, we relegate all proofs of the propositions to Appendix A.[5]

We model a representative firm that makes production decisions and maximizes profits. Total output (e.g., generation of electricity) is represented by Q and this output has a price p, such that $p = p(Q)$ and $p' \leq 0$. There are three types of output: production from natural gas x_M,

[5] The online Appendix can be accessed at http://environment.yale.edu/gillingham/GillinghamHuang_Appendix.pdf.

production from a source that has higher emissions than natural gas x_H (e.g., coal), and production from a source that has lower emissions than natural gas x_L (e.g., renewables). For simplicity, in the following text we refer to x_H as 'coal' and x_L as 'renewables.' We assume that each fuel source is associated with rates for emitting carbon and air pollutant j, where $j \in \{1,\ldots,J\}$. We normalize the emissions rate for x_M to unity, and denote the relative emissions rate of x_H as β for CO_2 and θ_j for other pollutant j such that $\beta \geq 1$ and $\theta_j \geq 1$. We further assume for simplicity that the emissions rate for renewables is zero.[6] Following the economic theory literature on energy markets (e.g., Holland et al., 2009; Gerarden et al., 2016), we let the cost functions for producing output be $C_i(x_i)$, $i \in \{L, M, H\}$ with $C_i' > 0$ and $C_i'' > 0$ (i.e., an increasing and convex cost function). We model the abundant natural gas scenario by assuming a savings in the marginal input cost of x_M, which is represented as a function of the natural gas supply S through the following relationship: $\tau = g(S)$ with $\tau' = \partial g(S)/\partial S > 0$.[7]

The efficient fuel portfolio and output production in the model apart from emissions (not accounting for any negative externalities) can be solved for using the following firm profit maximization problem:

$$\max_{x_L, x_M, x_H} pQ - \sum_i C_i(x_i) + \tau x_M . \tag{1}$$

The first-order conditions (FOCs) of the firm's profit maximization problem in (1) are:

[6] Of course, emissions factors for producing and installing renewables are not zero and at high levels of renewables there could be a need for backup, which may have emissions associated with it. Adding a non-zero emissions factor for renewables would add complication without fundamentally changing the intuition of our model.

[7] S can be thought of as vector representing the supply available for any price of natural gas.

$$
\begin{aligned}
&p - C_L'\left(x_L\right) = 0, \\
&p - C_M'\left(x_M\right) + \tau = 0, \\
&p - C_H'\left(x_H\right) = 0.
\end{aligned} \tag{2}
$$

The FOCs imply that, for a profit maximizing allocation, the marginal revenue of production equals the marginal cost from each fuel source.

The emissions of CO_2 and each other pollutant j from using the energy sources are represented by the following two equations respectively:

$$E_c = x_M + \beta x_H,$$

$$E_j = x_M + \theta_j x_H.$$

We are interested in the comparative statics from a change in the supply of natural gas S. We will begin with the implications for emissions, which are as follows:

$$\frac{\partial E_c}{\partial S} = \frac{\partial x_M}{\partial S} + \beta \frac{\partial x_H}{\partial S}; \tag{3}$$

$$\frac{\partial E_j}{\partial S} = \frac{\partial x_M}{\partial S} + \theta_j \frac{\partial x_H}{\partial S}. \tag{4}$$

The signs of (3) and (4) depend intuitively on how the use of natural gas and coal changes and the relative emissions rates β and θ_j for CO_2 and each other pollutant. This leads to the following result, which lays out the conditions under which we might expect the private market to reduce emissions with a shift in the supply of natural gas:

Proposition 1: *Under the privately efficient allocation of fuels (not considering negative externalities), the marginal emissions for CO_2 (pollutant j) with a change in the supply of natural* *gas S is positive if $1 \le \beta \le \overline{H}$ ($1 \le \theta_j \le \overline{H}$), and is negative if $\beta \ge \overline{H}$ ($\theta_j \ge \overline{H}$), where* $\overline{H} = \left(p'\left(C_L'' + C_H''\right) - C_L''C_H'' \right) \big/ p'C_L''$.

See Appendix A for the proof. Proposition 1 follows because abundant natural gas leads to the marginal cost of natural gas being lowered by τ, which increases natural gas consumption and decreases consumption of other resources (e.g., coal and renewables), and the resources have different emission rates. If increased emissions from natural gas dominate emissions reductions from coal or sufficiently cut into emission reductions from renewables, total emissions go up; otherwise, total emissions decline. Proposition 1 formalizes these conditions.

This first intuitive result lays the foundation for understanding how welfare may be affected from abundant natural gas. Conceptually, we would expect changes in consumer and producer surplus, and social costs from changes in carbon emissions and other air pollutant emissions. There may also be changes in welfare from water pollution and impacts on wildlife, but due to a lack of solid evidence on these externalities, we omit them from the quantitative analysis in the following sections.

Denote the marginal social cost of carbon as φ, the marginal damage of pollutant j as λ_j, and net monetized value for other externalities k (e.g., water pollution, methane leakage, etc.) as D_k. Then the change in total welfare on the margin with a change in S can be represented as:

$$\frac{\partial W^G}{\partial S} = \frac{\partial \int_0^{Q^G} p(Q)}{\partial S} - \sum_i \frac{\partial \int_0^{x_i^G} C(x_i)}{\partial S} + \varphi \frac{\partial E_c}{\partial S} + \sum_j \lambda_j \frac{\partial E_j}{\partial S} + \sum_k \frac{\partial D_k}{\partial S}, \tag{5}$$

where Q^G and x_i^G are the output quantities solved from the FOCs in (2) subsequent to a re-equilibration in the market after the change in S (*G* here simply refers to abundant natural gas).

Due to the changes in prices and quantities with the change in S, the area under the demand curve and above the cost curve(s) will change (first two terms on RHS). The net of these two terms will be positive, as the cost curves are shifting downwards. The last three terms on the RHS indicate the changes in externality costs. These may be positive or negative, depending on interactions in the energy system. Thus, welfare will improve if the abundant natural gas provides large benefits to consumers and producers that outweigh the externality costs. This equation also suggests that if abundant natural gas reduces overall emissions (consider Proposition 1), then the increased natural gas supply would be expected to increase social welfare as long as the other externality costs are sufficiently small.[8]

When we consider a case with both abundant natural gas and a climate policy, we see similar results. Consider a positive carbon price nationwide, either implemented through a carbon tax or tradable permit system. Let t be the carbon price (e.g., allowance price) measured in US$ per metric ton of CO_2. To remain sharply focused on climate policy, we do not model a price on other pollutants j, but adding this feature would not change the core intuition from our analytical discussion. We model the effect of the carbon price on equilibrium natural gas prices as $\tau_t = g(S;t)$, where $\tau_t' = \partial g(S;t)/\partial S > 0$.[9] The firm's profit maximization problem is then:

$$\max_{x_L, x_M, x_H} pQ - \sum_i C_i(x_i) + \tau_t x_M - t(x_M + \beta x_H), \tag{6}$$

and the associated FOCs from the above objective function (6) are:

[8] This follows because consumer surplus and producer surplus would both be expected to increase with an exogenous (free) shift in the natural gas supply. This rules out unusual general equilibrium impacts or unusual effects due to imperfect competition, under which it is theoretically possible for a different result to occur. We are also not modeling carbon capture and sequestration technology in this illustrative framework in order to focus on the key intuition.

[9] This flexible relationship allows us to sidestep questions of pass-through, which would only distract from the economics we are exploring.

$$\begin{aligned} &p - C_L'(x_L) = 0, \\ &p - C_M'(x_M) + \tau_t - t = 0, \\ &p - C_H'(x_H) - t\beta = 0. \end{aligned} \tag{7}$$

If the carbon price is set equal to the marginal damages, then the policy will perfectly internalize the externality from CO_2 emissions into the firm's decision-making process. On the other hand, if the carbon price is less than the marginal damages, the externality from CO_2 emissions is only partially internalized into the firm's decisions. We will focus our discussion on the case where the carbon price is less than the marginal damages of CO_2 emissions (such that $t < \varphi$), but we will briefly discuss a carbon price that perfectly internalizes the externality as a special case.

It can be shown that there is a threshold value of the emissions intensity—just as in Proposition 1—below which the marginal emissions of CO_2 and each other pollutant j increase and above which the marginal emissions decrease (see Appendix A). When there is a carbon price, however, there will be an entirely different set of equilibrium outcomes, as we will be on a different point on the supply curve for each fuel. The change in welfare in this pricing case (denoted by P) will then be given by:

$$\frac{\partial W^P}{\partial S} = \frac{\partial \int_0^{Q^P} p(Q)}{\partial S} - \sum_i \frac{\partial \int_0^{x_i^P} C(x_i)}{\partial S} + (\varphi - t)\frac{\partial E_c}{\partial S} + \sum_j \lambda_j \frac{\partial E_j}{\partial S} + \sum_k \frac{\partial D_k}{\partial S} \tag{8}$$

where Q^P and x_i^P are the output quantities solved from the FOCs in (7) after re-equilibration. The key difference between equation (8) and equation (5) is the addition of the carbon price, which reduces the externality from carbon emissions. If t is equal to φ, then the third term on the RHS is zeroed out, as the carbon externality would be fully internalized. Again, a key point is that the third to fifth terms are critical for signing the welfare implications of the change in S under carbon pricing. If the net change in externalities is negative due to the change in S, then we can unambiguously confirm that welfare will increase. This simple exposition lays the theoretical groundwork for our numerical simulation modeling in the next sections.

4 METHODOLOGY

While theory can be illuminating, in this study we are especially interested in quantitative estimates of energy production, energy consumption, energy prices, emissions, and welfare effects of the abundant natural gas scenario. For quantitative estimates, we need a model that both covers a wide range of energy markets and models dynamic behavioral responses by firms in these markets. We are also particularly interested in understanding the spatial distribution of environmental and welfare consequences, which requires a model with granular and detailed modeling of energy markets and demand. Further, such a model must have all of the outputs of interest at a sufficiently granular level. The National Energy Modeling System (NEMS) is an ideal candidate for our research agenda.[10]

4.1 Yale-NEMS

Yale-NEMS is an integrated energy-economy modeling system, built and implemented by the U.S. Energy Information Administration (EIA) and currently hosted on a Yale server. For decades now, NEMS has been used to evaluate a variety of existing and proposed energy policy alternatives (e.g., Nogee et al., 2007; Banks and Force, 2008; Fischer, 2010); the mitigation of greenhouse gases (e.g., Palmer et al., 2010; Goulder, 2010; Wilkerson, 2014); the implications of increased use of renewable energy (e.g., Bernow et al., 1997; Deyette and Clemmer, 2004; Chen

[10] While other models with similar capabilities exist, such as ICF Consulting's Integrated Planning Model (IPM), such models are proprietary. MARKAL is a model commonly used by EPA and some academics, which has similar detail to NEMS, but is an energy systems planning model (i.e., energy system costs are minimized), rather than a general equilibrium economic model, and we believe that the general equilibrium feature of NEMS (an approach with intellectual antecedents going back to Leon Walras) is particularly important for welfare analysis.

et al., 2009); the impact of improved energy efficiency (e.g., Koomey et al., 2001; Scott et al., 2008; Auffhammer and Sanstad, 2011; Cox et al., 2013); and the role of U.S. energy in international markets (Bordoff and Houser, 2014).

NEMS consists of 13 modules that cover all major fuel supply markets, conversion sectors, end-use demand markets, macroeconomic activity, and links to international energy markets. NEMS projects energy market movements for around 25 years into the future, including consumption, production, imports, exports, substitution, and prices subject to a set of economic, resource availability, technology, behavior, and demographics assumptions. To address regional heterogeneity, NEMS disaggregates the nation into regions for each module based on data availability and model functionality.

Because we are interested in the effects of abundant natural gas and its interaction with climate policy, the following discussion will focus on how the natural gas market and climate policy are modeled within NEMS.[11] In general, the U.S. natural gas market is modeled by equilibrating supply and demand, from which market clearing is obtained as the model is solved.

Demand for natural gas as well as other major fuels (e.g., coal, liquid fuels, nuclear, and renewables) is driven by macroeconomic, demographic, climate, technological, and structural factors. These are modeled in the residential, industrial, commercial, transportation demand modules, liquid fuels market module, and the electricity market module (Brown et al., 2010). The model allows for fuel substitution based on demand elasticities, cost effectiveness, and resource availability. Demand for natural gas also includes endogenous demand for LNG exports and exogenous demand across the Mexican and Canadian borders. For LNG exports, the model

[11] Detailed documentation for NEMS modules can be found at: https://www.eia.gov/outlooks/aeo/nems/documentation/.

projects a representative natural gas price in sold destinations Europe and Asia. The model then evaluates the long-run economic profitability of constructing additional LNG liquefaction facilities. The utilization rate of the LNG facilities depends on prices and costs of transporting natural gas.

Natural gas electric generating capacity is built based on a variety of factors, such as the timing of electricity demand increase, utilization of capacity, capital cost of construction, and variable cost of operation. Yale-NEMS includes a stylized model of electricity generation dispatch in the electricity market module (EMM) based on the merit order. Non-dispatchable intermittent generating capacity, such as wind or solar, generates electricity based on weather conditions and NEMS assures that electricity demand is met by provisioning sufficient dispatchable generation, including natural gas (EIA 2009). As an equilibrium model, Yale-NEMS accounts for how adding non-dispatchable generation influences electricity prices, but it is not intended nor designed for questions relating to the market value of renewables (e.g., Hirth, 2013; Hirth, 2015; Green and Léautier, 2015).

On the supply side, there is a separate oil and gas supply module (OGSM) that projects the availability of domestic crude oil and natural gas production from onshore, offshore, Alaskan reservoirs, and Canadian imports at the play level. The natural gas resource types in OGSM are split into two categories: conventional and unconventional, with unconventional further disaggregated into tight gas, shale gas, and coalbed methane. Each production location is associated with a supply curve, determined by a set of factors: ultimate recoverable resources; finding and success rates; and cost reduction due to technology progress (Brown et al., 2010). The key assumption of OGSM is that higher market prices incentivize production through existing fields and exploring more costly areas, subject to policy regimes and resource accessibility.

Natural gas demand and supply are then connected in the natural gas transmission and distribution module (NGTDM). This module covers the domestic supply/demand relationships across regions, Canadian, Mexican, and LNG supply/demand components, and flows among those. The transmission and distribution network in NGTDM is an aggregate representation of the real natural gas pipeline system in the U.S., which can be expanded endogenously if the revenue from construction is higher than the costs.

Carbon dioxide emissions are modeled in the emissions policy submodule, which estimates emissions based on fuel consumption, combustion fraction, emissions factors, and carbon mitigation technologies. Carbon policies, such as a cap and trade or a carbon tax, generally introduce a surcharge on energy prices based on the emissions factors.

4.2 Scenarios

Each year, EIA develops a widely publicized Annual Energy Outlook (AEO) reference case based on a comprehensive updating of policy and technology assumptions. The AEO reference case is heavily used in both government and private sector decision-making as a plausible future scenario given the information known today and EIA's expert judgment.[12] We use AEO2017 as our reference case (EIA 2017a). We propose two alterative scenarios that take the reference case as a starting point: (1) a scenario with abundant natural gas and (2) a carbon pricing policy. We further explore a third scenario that combines elements from these two scenarios.

4.2.1 Reference case

AEO2017 was published in January 2017. It presents a time path of key U.S. energy market variables projected out to 2050 (EIA 2017a). AEO2017 departed from many previous AEOs by

[12] The AEO reference case has also been widely critiqued as a forecast (Auffhammer, 2007), although staff at EIA would argue that it is being misused if it is used as a forecast.

including a projection with and without the Clean Power Plan (CPP). The CPP was an Obama Administration policy, finalized in 2015, that sets a target to reduce CO_2 emissions from the electric sector by 32% below 2005 levels by 2030 (EPA, 2015). On March 28, 2017, President Trump signed an executive order instructing EPA to review the CPP,[13] and on October 10, 2017, EPA Administrator Scott Pruitt signed a rule to start a formal process repealing the CPP. Although potential legal challenges are still pending, there is a strong likelihood that the CPP will be substantially less stringent than the 2015 final rule, and thus for our study, we are using the AEO2017 "No CPP" projection as our reference case.

Every AEO reference case aims to include all state and federal policies and regulations that are currently in place, and it assumes that they remain in place until their sunset dates. No new policies are assumed to be enacted going forward. This includes any newly implemented legislation or rulemakings that have been finalized but not yet implemented. For example, California state law SB-32 (limiting state-wide greenhouse gas emissions to be 40% below the 1990 levels by 2030) and the second phase of federal fuel economy standards for medium- and heavy-duty vehicles are not in the AEO reference case (EIA 2017a).

AEO2017 assumes a technically recoverable resource (TRR) of proved reserves and unproved resources for natural gas of 2,355 Tcf. The total shale gas resources are assumed to be 1,025 Tcf (EIA 2017b). These TRR estimates are compiled by EIA from the latest available production data and other information from government agencies, industry, and academia. To account for new discoveries, Yale-NEMS also allows technology improvements to add potential resources to TRR. In addition, it captures the impact of technology improvement on production cost reduction and growth in resources (EIA 2017b). For instance, for shale natural gas, the annual

[13] Source: https://www.nytimes.com/2017/03/28/climate/trump-executive-order-climate-change.html.

average rate of technological improvement is represented by -1% for drilling costs and -0.5% for operating costs.

4.2.2 Abundant natural gas supply

For our abundant natural gas scenario, we found the most optimistic (but still realistic) estimates of natural gas resources available. The Potential Gas Committee (PGC) recently produced a study with estimates of U.S. resources disaggregated at a regional level using the most recent available geologic data and statistical methodologies (PGC 2016).[14] Earlier estimates from the PGC have also been used in the academic literature (Brown et al., 2009; Brown and Krupnick, 2010; Brown et al., 2010). We adopt the PGC estimate of 2,817 Tcf of total U.S. unproved natural gas resources as of year-end 2015, with 1,797 Tcf of shale gas resources.[15] This is a substantially larger unproved resource and we implement this in Yale-NEMS by shifting out the supply curve for unproven natural gas resources. This scenario holds proved reserves the same as EIA's estimates. To implement this scenario, we compare the resource estimates of PGC to the EIA reference to compute a scale coefficient for each production region and each resource type (conventional natural gas, tight gas, coalbed methane, and shale gas), and then adjust resource upper bounds and supply curves for plays in production regions by the computed scale coefficients.

4.2.3 Carbon pricing policy

For this study, we implemented a moderate economy-wide carbon pricing policy that ramps up slowly over time. While it is impossible to know what a future national carbon pricing policy would look like, we chose this policy as an example of what a moderate carbon price would imply.

[14] Potential Gas Committee is a non-profit group of around 80 volunteer geoscientists and engineers. It produces reports for assessing technically recoverable U.S. natural gas resources every two years since 1964.

[15] EIA's AEO2017 also investigates a low and a high oil and gas resource scenarios, in which they allow resources to be boosted or downscaled uniformly across regions. Our study differs from these scenarios in that (a) our numbers are slightly different, (b) we do not scale up oil resources, and (c) we apply the regional estimates of natural gas resources to census regions in Yale-NEMS.

The carbon price we implemented begins in 2020 at a low level—approximately \$2/ton CO_2 in 2016 U.S. dollars—and increases linearly to \$46/ton CO_2 (again in 2016 dollars) in 2040. The carbon price remains constant thereafter. This carbon price path is illustrative and is substantially below the central case path of the social cost of carbon (SCC) estimated by the Obama Administration Interagency Working Group on the Social Cost of Greenhouse Gases (IWG, 2016). While there is considerable uncertainty in the value of the SCC, taking the central case IWG price path as given would imply that our modeled carbon pricing path would only partly internalize the externality from carbon dioxide emissions.

5 PRIMARY RESULTS

We now turn to presenting a selected set of results from Yale-NEMS for the four scenarios: the AEO2017 reference, abundant natural gas, carbon pricing, and abundant natural gas under the carbon pricing policy. All dollar values are in 2016 dollars.

5.1 Natural gas market

Table 1 shows total natural gas production for each scenario in five-year time steps out to 2050. When there is abundant natural gas (either with or without a carbon price), natural gas production is substantially greater, with roughly a 25% increase relative to the reference case after just a few years of adjustment. The projected Henry Hub natural gas prices are shown in Figure 2.[16] This figure illustrates that natural gas is roughly 25% cheaper in the abundant natural gas scenario starting around 2020 all the way to 2050. The natural gas price in the carbon pricing scenario is the post-tax price, and accordingly, it is above the reference case. The abundant natural gas scenario generally has lower natural gas prices without carbon pricing. The only exception is

[16] See Table B.1 in Appendix B for the underlying data in Figure 2. More generally, we provide the tables for each of our figures in Appendix B.

that the abundant gas case with carbon pricing is lower in later years after 2042. A major reason for this feature of the results is that when there is a carbon price, there is more investment in renewables earlier on, leading to lower prices and more generation from renewables (through endogenous technological change) in later years. This additional renewables capacity is sufficient to depress demand for natural gas, leading to an equilibrium with lower natural gas prices. We will see this phenomenon carrying through to our emissions results as well.

Figure 3 shows projected total energy consumption in trillions of Btus for natural gas, coal, and renewables. We calculate total energy consumption as the sum of energy consumption in the residential, transportation, commercial, industrial, and electric power sectors.[17] Under the abundant gas case, natural gas consumption is sharply higher than the reference case by up to 17% in 2050. The increase in natural gas consumption comes primarily from the substitution away from coal and renewables. Notably, renewables capacity is slightly lower in the abundant gas case, by 12% in 2050. While coal consumption drops under the abundant natural gas scenario, there is a much more substantial decrease in coal consumption in the carbon pricing scenario: a 70% reduction from the reference. This decline in coal is exaggerated even further when there is abundant natural gas in concert with a carbon price. Renewables show the largest increase under a carbon pricing policy, and somewhat smaller of an increase when there is abundant natural gas along with the carbon pricing—due to the increased competition from natural gas.

5.2 Air pollutant emissions

Energy-related CO_2 emissions are shown in Figure 4. A first observation is that CO_2 emissions in the abundant natural gas scenario are very similar to emissions in the reference case.

[17] There is consumption for other sources such as liquid fuels and nuclear. These sources are not shown in the figure because they do not vary significantly across the scenarios. The full consumption data are available as part of the online Appendix.

This ties in closely with our theoretical model, in that emissions from a scenario with abundant natural gas can increase or decrease depending on the emissions rates and the substitutions that occur throughout the energy system. We see that until about 2045, energy-related CO_2 emissions in the abundant natural gas scenario are lower than the reference case, but only by a small margin. After about 2045, energy-related CO_2 emissions in the abundant natural gas scenario are actually *higher* than emissions in the reference—again due largely to the lower renewable energy capacity in the abundant natural gas case. This result alone raises questions about the notion that abundant natural gas will substantially lower emissions as a bridge to a low-carbon future.

In contrast, the carbon pricing scenario leads to substantially lower energy-related CO_2 emissions. Until around 2038, energy-related CO_2 emissions are even lower when we add a carbon pricing policy to the abundant natural gas scenario, largely due to the substitution from coal to natural gas. However, after 2038, this pattern switches, as the larger increase in renewables in the carbon pricing policy scenario without abundant natural gas implies lower energy-related CO_2 emissions than the carbon pricing scenario with abundant natural gas. In short, the availability of abundant natural gas implies some substitution from renewables to natural gas, thus increasing energy-related CO_2 emissions.

Figure 5 presents emissions for three important air pollutants from the electric power sector: sulfur dioxide (SO_2), nitrogen oxides (NO_x), and mercury. While this is by no means a complete list of pollutants from burning fossil fuels, it captures three of the major pollutants that cause health effects. Other major pollutants are not modeled in NEMS including ($PM_{2.5}$ and PM_{10}),[18] volatile organic compounds (VOC), and ammonia (NH_3). In the next section, we will discuss how we

[18] $PM_{2.5}$ represents small particulates that are less than 2.5 microns in size, while PM_{10} represents those that are smaller than 10 microns but larger than 2.5 microns.

incorporate these additional pollutants into our welfare evaluation. It is also worth pointing out that the estimates in Figure 5 are at an aggregate level, but these air pollutants are local or regional pollutants with local or regional air quality implications (Mauzerall et al., 2005). We use regionalized estimates in our welfare calculations below.

The results in Figure 5 show that for all three pollutants, emissions decline in the abundant natural gas scenario relative to the reference case. This follows because natural gas is a cleaner fuel than coal and there is more substitution from coal to natural gas than from cleaner fuels, like renewables, to natural gas. The lowest time path of emissions is the carbon pricing scenario with abundant natural gas, which is the case because natural gas has very low emissions rates for these pollutants, so substituting towards natural gas is almost as effective at reducing these pollutant emissions as substituting toward renewables. This again is as would be predicted based on our theoretical discussion above.

Thus, while abundant natural gas may not provide a clear bridge to a low-carbon future, it would reduce emissions of many air pollutants that lead to adverse health effects—although not to the same degree as the modest carbon pricing scenario that we modeled.

5.3 Sensitivity analysis

We perform a variety of robustness checks to examine the sensitivity of our primary results to various other reasonable assumptions. Specifically, we vary a set of parameters relevant to natural gas demand and supply, and then compare the results to the abundant gas case. Each identified factor consists of a high and a low case.

We began by exploring factors that influence natural gas demand. The first factor we modify is the fuel efficiency of fossil fuels, as this will determine the degree of fuel substitution.

Similarly, we adjusted the learning rates for renewables. We also adjusted the international demand for liquefied natural gas exported from the U.S. by modifying the parameter governing future capacity expansion for liquefaction terminals.

We also examined factors that influence natural gas supply. These include parameters governing the technology advancement associated with natural gas production and the parameter related to fuel pipeline capacity expansion.

The results of the sensitivity analysis generally confirm our findings (see Appendix E for details). The assumed rate of technology advancement in natural gas production appears to be the most important factor that we examined for changing the results. In a case with high natural gas technology advancement[19] (50% higher than in the abundant natural gas scenario), we find 12% higher natural gas production, 20% higher gas consumption, 0.3% lower CO_2 emissions, and 21% lower SO_2 emissions by 2050 when compared to the abundant natural gas scenario. In contrast, in a low natural gas technology advancement case (50% lower than in the abundant natural gas scenario), we find 10% lower natural gas production, 0.2% higher CO_2 emissions, and 12% higher of SO_2 emissions in 2050. These results underscore the importance of assumptions about technological change.

Another parameter that turns out to be relatively important is the assumption about the potential for future LNG export terminal expansions. The high case of LNG capacity expansion cost (20% higher than the abundant natural gas case) leads to 2% higher natural gas production, 1% lower gas consumption, 0.1% lower CO_2 emissions, and 1.4% higher SO_2 emissions. The low case of LNG capacity expansion cost (20% lower than the abundant natural case) provides results

[19] The technological advancement parameter is a percentage adjustment factor that reduces production costs and increases the productivity of natural gas production in OGSM in Yale-NEMS.

with similar magnitudes, but with the opposite signs. Besides these two parameters, all of the other factors we examined do not appear to be influential in the results—in fact, the high and low scenarios we ran show only small changes (on the order of 0-0.001%).

6 WELFARE IMPLICATIONS

While the results so far tell a compelling story about how the energy system and emissions would change with abundant natural gas, from an economics perspective we are especially interested in the welfare implications of these results. Accordingly, we calculate the change in welfare for the two abundant natural gas scenarios (with and without carbon pricing) based on equations (5) and (8) from our theoretical discussions. The welfare effects can be categorized into the following: changes in consumer and producer surplus, changes in CO_2 externalities, and changes in externalities from other air pollutant emissions. Due to challenges in quantification, we do not estimate additional potential negative welfare effects, such as the consequences of frac water contamination, methane leakage, or local air pollution from diesel trucks used in the natural gas extraction process. However, we will provide a discussion of these effects after our quantification of the results to get a ballpark sense of their magnitude. Similarly, we only quantify the CO_2 and air pollutant emissions from coal and renewables and do not quaantify other potential environmental impacts. This section is organized as the following: we will first discuss how we calculated each component of welfare, then we present the national welfare results, and we follow this with disaggregated regional level results.

6.1 Changes in consumer and producer surplus

To estimate the changes in consumer and producer surplus, we assume locally linear supply and demand functions for ease of computation whenever it is necessary (Small, 2010; Krupnick and McLaughlin, 2011; Gillingham, 2013). Appendix C provides a graphical representation of the changes and re-equilibration that we model to calculate the welfare effects. We calculate change in welfare for three major fuels—natural gas, coal, and liquid fuels—that are consumed in the industrial, commercial, residential, transportation, and power sectors. Any intermediates (e.g., electricity from the power sector) are not included in our welfare calculation to avoid double-counting.[20]

Mathematically, what we are calculating can be described as follows. Denote p_0, Q_0, and $S_0(Q)$ as equilibrium price, quantity, and supply functions associated with the reference case. Similarly, denote p_1, Q_1, and $S_1(Q)$ as those for the abundant natural gas scenario. Thus, the changes in consumer and producer surplus are computed as:

$$\Delta CS^G = -(p_1 - p_0)Q_1 + \frac{1}{2}(p_1 - p_0)(Q_1 - Q_0), \tag{9}$$

$$\Delta PS^G = \left(p_1 Q_1 - \int_0^{Q_1} S_1(Q)\,dQ\right) - \left(p_0 Q_0 - \int_0^{Q_0} S_0(Q)\,dQ\right). \tag{10}$$

For the natural gas market, we assume a linear demand curve and non-linear supply function for welfare calculation for each modeled scenario (reference, abundant natural gas, carbon pricing, abundant natural gas under carbon pricing). The resulting consumer and producer surplus estimates are then computed based on equations (9) and (10).

For coal and liquids fuels markets, we use a similar formulation as for natural gas markets. We use the reference case and re-equilibrated price and quantity output estimates from the Yale-

[20] One caveat to the approach that both we and others in the recent literature have followed is that each market is treated individually, so we do not compute welfare in all markets. Thus, the assumption is that any cross-market effects to other markets are considered to be negligible, keeping the focus on the primary markets directly affected. Given the difficulty of modeling pre-existing distortions, we follow other previous welfare analyses using NEMS and ignore such distortions. This includes pre-existing subsidy or renewable portfolio policies (to the extent that they are distortions).

NEMS simulations to estimate the slopes of demand and supply curves. Under the carbon pricing policy without abundant natural gas, we model a supply curve shift upwards, from which the re-equilibrated price-quantity pair, as well as data on the increased cost due to carbon pricing, are used to approximate the slopes of demand and supply curves. Then, the estimated slopes are used to estimate linear demand and supply curves for each modeled scenario that pass through the resulting price-quantity pair, which allows us to further estimate consumer and producer surplus, as shown in Appendix C. For the scenarios with carbon pricing, we account for the tax revenue separately from consumer and producer surplus, allowing us to be agnostic as to how the revenue is redistributed.

6.2 Monetized CO_2 emissions

For monetizing CO_2 emissions, we adopt the central case path of the SCC published by IWG (2016). Without carbon pricing policy, the change in monetized externalities from CO_2 emissions due to abundant natural gas is estimated by multiplying the SCC by the change in absolute CO_2 emissions across the projected years. Under carbon pricing, since the externalities from CO_2 are partially internalized by our path of carbon prices, the remaining externalities are estimated by replacing the SCC with the difference between the SCC and the carbon price.

6.3 Monetized pollutant emissions

We calculate the change in welfare due to the changes in air pollutant emissions from fossil fuel combustion by applying estimates of marginal damages per unit of emission to the Yale-NEMS results on changes in emissions.

Yale-NEMS models three types of pollutants: SO_2, NO_x, and mercury, as was shown in Figure 5. To evaluate a more complete set of pollutants, we adopt a simplified method to estimate the emissions for $PM_{2.5}$, PM_{10}, VOC, and NH_3 based on the EPA 2014 National Emissions

Inventory (NEI) data.[21] The NEI data provide emission levels for the above four pollutants in the U.S. in 2014. For the purposes of this calculation, we assume no technology change over time and extrapolate pollutant emissions after 2014 as constant proportions relative to energy consumption. While this is clearly a simplification, it is a reasonable assumption that facilitates useful calculations.

There are a series of studies assessing damages caused by air pollutants in the U.S. (Muller and Mendelsohn, 2007; Muller and Mendelsohn, 2009; Muller et al., 2011; Jaramillo and Muller, 2016). We use the regional marginal damage data from Muller et al. (2011) for SO_2, NO_x, $PM_{2.5}$, PM_{10}, VOC, and NH_3, which are computed from an integrated assessment model, and monetary estimates of mortality and morbidity risks.[22] As for mercury, the marginal damage data are based on Spadaro and Rabl (2008).

6.4 Other externalities

It is worth noting that the above categories for welfare evaluation are not exhaustive. A variety of environmental concerns have been raised regarding shale gas development. For example, some of the most controversial impacts to date are water depletion and contamination (Nicot et al., 2014; Mason et al., 2015; Hausman and Kellogg, 2015). Water contamination can be related to chemical fluids spills and improper wastewater management (Jackson et al., 2014). In addition, the shale gas extraction and transportation process can lead to the emission of both air and water toxins (Field et al., 2014). All of these effects can have adverse consequences for human health. For instance, Currie et al. (2017) found evidence for negative health impacts in exposure to

[21] Data source: https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data.
[22] Data from the study can be downloaded at: https://www.aeaweb.org/articles?id=10.1257/aer.101.5.1649.

fracking sites including significant declines in average birth weight of babies and several other measures of baby health.

Other welfare impacts include increased traffic accidents (Graham et al., 2015), road damages by heavy trucks (Abramzon et al., 2014), and local disamenities in terms of noise and crime (Newell and Raimi, 2015). Methane leaks from natural gas production and pipelines (primarily, but not exclusively local distribution pipelines) can also contribute to climate change (Hausman and Muehlenbachs, 2018). A more detailed review for positive and negative externalities caused by increased development of shale gas can be found in Mason et al. (2015).[23]

While it is clear that these additional externalities exist, our review of the literature provided surprisingly few estimates of the magnitude of these externalities. Some of the only estimates that are useful for creating a ballpark estimare are from Siikamäki and Krupnick (2014). They estimate an average willingness to pay (WTP) of $24 per year per household to remove pollution in 1% of the Texas state's surface water bodies, and around $33 per year per household to solve the pollution problem for 1,000 groundwater wells associated with shale gas production. We use these estimates to get a sense of the magnitude of these externalities in the next section.

6.5 National summary

Table 2 provides a national summary of welfare results, disaggregated into the four above quantifiable categories. We present results with different comparisons for 2030 and 2050, using both the reference case and the carbon pricing scenario. The first and second columns show the comparison of the abundant gas case to the reference, showing total welfare gains of 49 billion dollars in 2030 and 100 billion dollars in 2050. Most of these improvements in welfare come from

[23] There are of course also externalities from other sources of generation, including coal and renewables. Fully accounting for these additional externalities may alter the net welfare estimates.

increased consumer surplus due to lower natural gas prices. While there are large consumer surplus gains, we find modest *losses* in producer surplus. This result is consistent with Hausman and Kellogg (2015) who look retrospectively at the welfare effects of the shale gas boom. The main reason for this loss is due to inframarginal producers, who would have produced anyway and now receive a lower natural gas price for their production. In contrast, the marginal producers clearly gain, but it turns out that empirically this is outweighed by the losses to the inframarginal producers.

When we are in a world with carbon pricing, the addition of abundant natural gas again improves consumer surplus but decreases producer surplus in a similar way, as is shown in the third and fourth columns (note that the tax revenue is assumed to be redistributed without loss or gain and thus cancels out of this welfare calculation; in reality, the method of redistribution can influence the welfare implications, but this is beyond the scope of our analysis). We can also compare the carbon pricing results to the reference case as a benchmark (columns five and six), showing that carbon pricing leads to a clear improvement in welfare, which is less than the improvement in welfare from abundant natural gas in 2050. This improvement in welfare stems from reducing externality costs and comes about despite a loss in consumer surplus from higher energy prices. Finally, columns seven and eight compare the reference case to the scenario with both abundant natural gas and carbon pricing. This shows the greatest improvement in welfare, underscoring that while carbon pricing improves welfare, there would be an even greater improvement in welfare if there is also abundant natural gas.

The above calculations deserve an important caveat for there is no quantification of other externality costs. While these additional costs have not yet been satisfactorily quantified in the literature, we can use the estimates from Siikamäki and Krupnick (2014) to better understand how large the issue may be. Specifically, we can calculate how many households would have to live around shale gas development sites for our welfare analysis to show losses in welfare. With our net benefit estimates due to abundant natural gas in 2050 ($100 billion), assuming 5% of surface water and 100,000 groundwater wells are polluted nationwide, by applying the Texas WTP to other states, we calculate that it would take 30 million households to live around shale gas development sites to forfeit the benefits. We deem this as highly unlikely, suggesting that the benefits of abundant natural gas far outweigh the costs—at least based on these estimates of the externality costs. We recognize that it is possible that methane leaks (particularly from the distribution system) and occasional disasters, like the Aliso Canyon, CA gas leak in 2015, further tip the balance. Indeed, some studies claim that methane leakage damages from natural gas operations may completely outweigh the gains from natural gas usage (e.g., Howarth et al., 2011; Howarth, 2015). However, on the contrary, others argue that methane leakage is unlikely to substantially undermine the benefits (e.g., Cathles et al., 2012; Levi, 2013). One important qualification to this debate is that if the leaks are in the local pipeline distribution system, a switch in electricity generation away from natural gas and to renewables may not reduce these external costs much. The bottom line from our results is that the externality costs from the water pollution and methane leaks would have to be quite large to counter the consumer surplus benefits (and to a much lesser degree, climate benefits) from abundant natural gas.

6.6 Regional results

Figure 6 shows the 2030 and 2050 changes in consumer and producer surplus by census region (the level of Yale-NEMS granularity). We include all changes to consumer and producer surplus from the natural gas, liquid fuels, and coal markets. We compare the abundant natural gas scenarios to both the reference case or the carbon pricing scenario.[24] Of course, we recognize that

[24] Appendix D provides additional regional results comparing the carbon pricing scenario to the reference case.

the shareholders of natural gas and other firms may not be concentrated in the regions where the production occurs, so the regional disaggregation of producer surplus should be taken with a grain of salt. For example, it is quite possible that New York City receives a large share of the producer surplus from natural gas extraction, due to many wealthy holders of assets, even if no actual production occurs in the city.

Figure 6 shows that there are large gains in consumer surplus from abundant natural gas, and that these gains are primarily concentrated in the region around Texas (major producing states) as well as the West Coast (largely due to high energy prices in California). Similarly, the region around Texas and along the West Coast also gain substantially in consumer surplus from abundant natural gas with carbon pricing—largely due to the fact that the region around Texas is a major natural gas producing region and California has relatively high energy prices.

Broadly, we see that the gains in consumer surplus from abundant natural gas are similar when compared to both the reference case and the carbon pricing scenario, suggesting that even if we have carbon pricing, there would still be large consumer surplus gains from abundant natural gas. In Figure 6 we also see that the changes in producer surplus from abundant natural gas tend to be much smaller than the gains in consumer surplus. The location of the losses appears to be centralized in the region around Texas. We attribute this to the concentration of inframarginal fossil fuel production in that region (again noting the caveat that shareholders may live elsewhere).

The regional changes in monetized damages for the major air pollutants are shown in Figure 7. These results are striking. The upper Midwest region far and away receives the largest gains from reduced air pollution damages (over 4 billion dollars by 2030), followed by the Middle Atlantic region (1 billion dollars). Both of these regions have high populations exposed to air pollutant emissions from coal-fired generation, and abundant natural gas leads to large reductions in this pollution, thus leading to large health benefits and welfare improvements. When there is already a carbon pricing policy in place, the benefits from reduced air pollution due to abundant natural gas are slightly smaller due to the fact that the carbon pricing has already improved the air quality.

The change in total welfare by region is displayed in Figure 8. These estimates include all of the categories in Table 2, including changes in uninternalized damages from CO_2 emissions (these CO_2 impacts are spread evenly across all regions). Comparing Figure 8 to Figure 6, we immediately see that the change in total welfare is primarily driven by consumer surplus. While the change in welfare is positive for all regions in both 2030 and 2050, we see that the largest gains in total welfare from abundant natural gas accrue to the region around Texas and the West Coast. These results underscore that while abundant natural gas leads to welfare benefits for the U.S., these benefits are far from evenly distributed.

7 CONCLUSIONS

Using a theoretical model and Yale-NEMS, we evaluate the impacts of potential increased natural gas supply and the interaction with a climate regulation in terms of CO_2 and air pollutant emissions and welfare consequences. First, we conclude that although abundant natural gas supply results in welfare gains both with and without carbon pricing scenarios, it does not reduce CO_2 emissions significantly over the projected period. This is because cheaper natural gas replaces not only coal but also renewables. On the other hand, natural gas is relatively effective in reducing air pollutions from burning fossil fuels. This implies that abundant natural gas should not be seen as a “bridge” to a low-carbon future, but rather as a source of welfare improvements. Second, climate policy—such as a carbon pricing policy—reduces CO_2 and air pollutant emissions, reaching even lower emission levels when combined with increased gas supply in the market.

A major contribution of this work is to estimate the economic welfare impacts of abundant natural gas. We find large potential welfare gains from abundant natural gas due to increases in consumer surplus (i.e., lower prices of energy) and reduced air pollutant emissions due to a substitution of natural gas for coal. While nearly all regions benefit—regardless of whether there is carbon pricing or not—we find that the greatest benefits accrue to the region around Texas and the West Coast.

A major caveat to these results is that we cannot quantify the loss in welfare due to methane leaks or local environmental degradation. Our calculations based on previous literature suggest that local environmental degradation is likely to be much smaller than the welfare benefits. Relatedly, we do not model other possible environmental costs of coal and renewables. But we acknowledge that it is possible, however unlikely in our view, that these factors could tip the cost-benefit analysis.

We should further mention that the results here are based on one of the best energy-economic modeling tools available—the NEMS platform—but within any large-scale energy model there are always many assumptions and parameterizations that rely on the expert judgment of the modelers. While we addressed what we found to be the most important of these key assumptions in our sensitivity analysis, there are many others that could be explored, including interactions between different possible paths of future energy policy, leaving open much room for future research.

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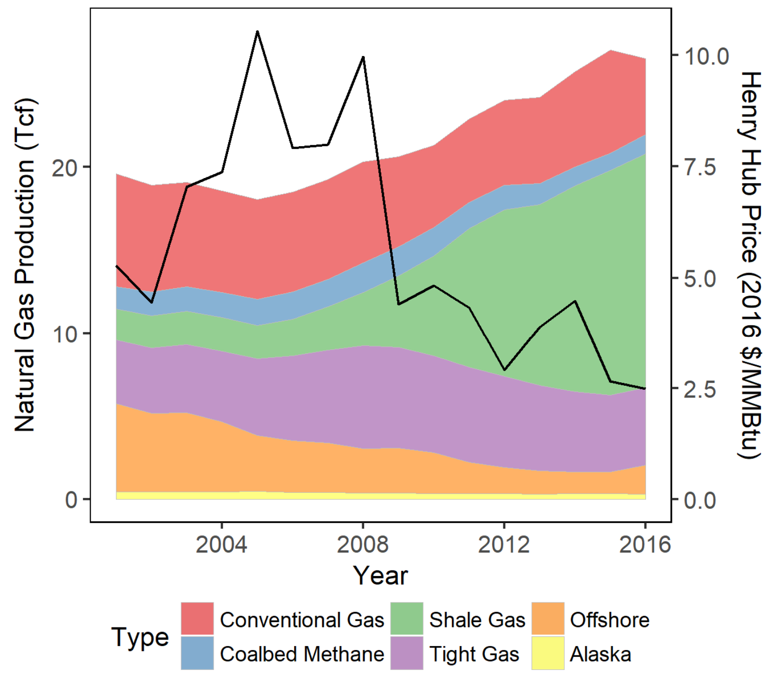

Figure 1: Historical U.S. natural gas production and Henry Hub prices.
Notes: the areas represent production and the dotted line represents price. (Data source: EIA)

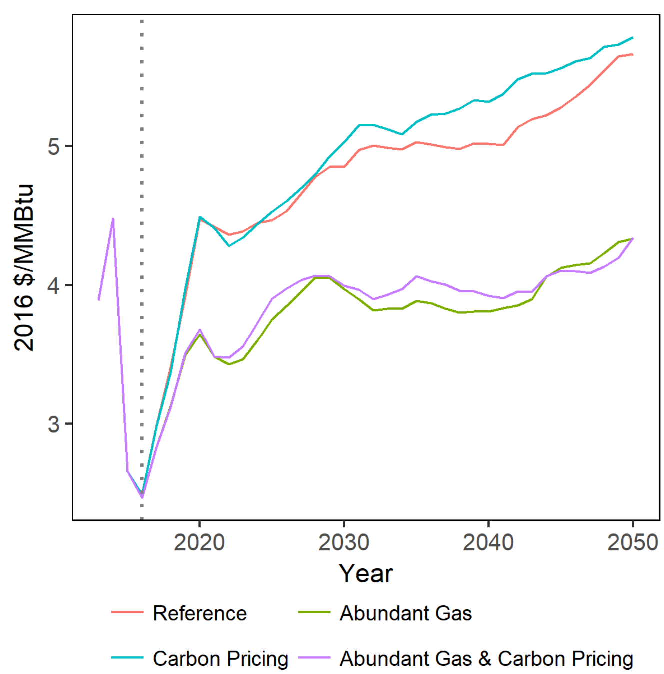

Figure 2: Projected natural gas Henry Hub prices.
Notes: the vertical dotted line separates historical and projected data.

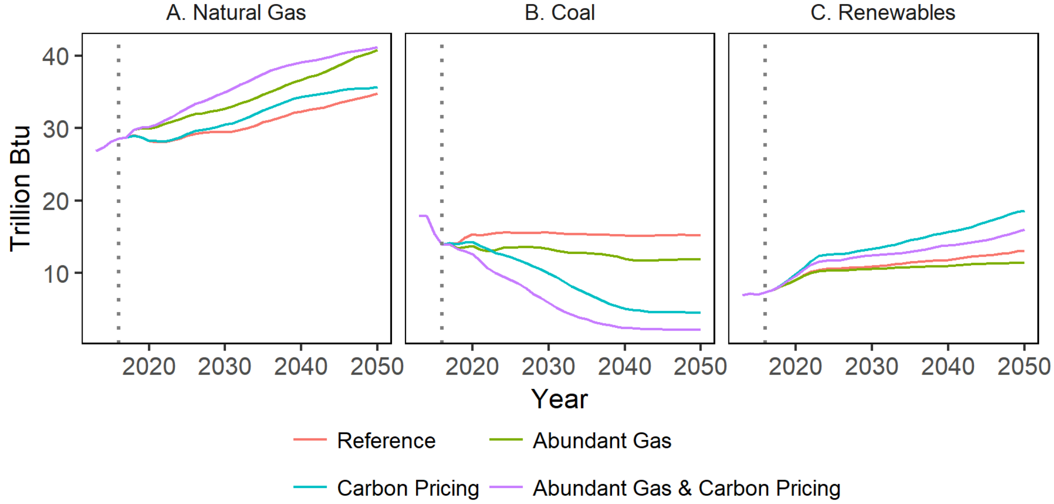

Figure 3: Projected U.S. energy consumption.
Notes: the vertical dotted lines separate historical and projected data.

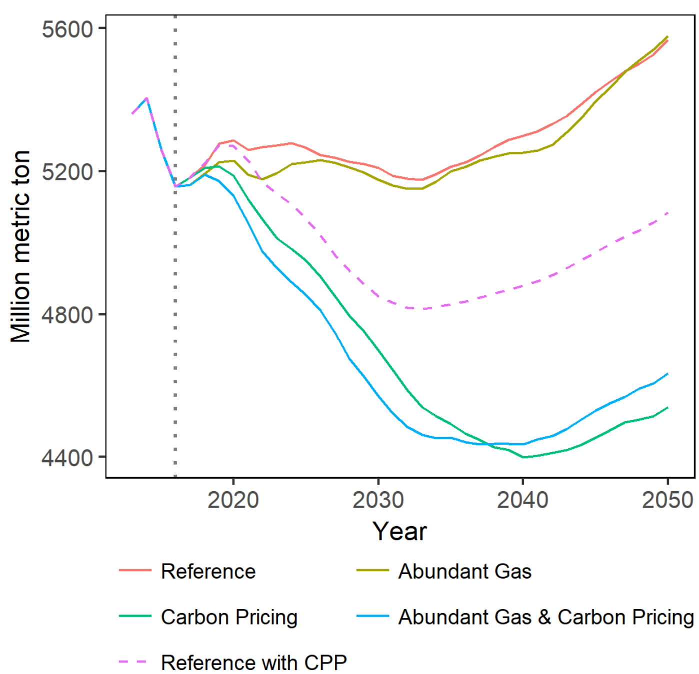

Figure 4: Projected energy-related CO_2 emissions.
Notes: the vertical dotted line separates historical and projected data.

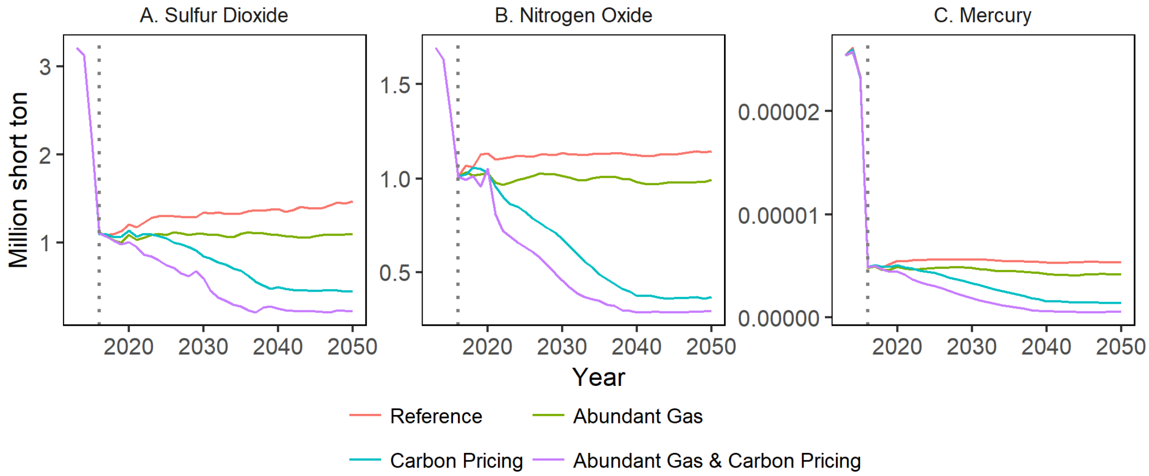

Figure 5: Projected pollutant emissions from the electric power sector.
Notes: the vertical dotted lines separate historical and projected data.

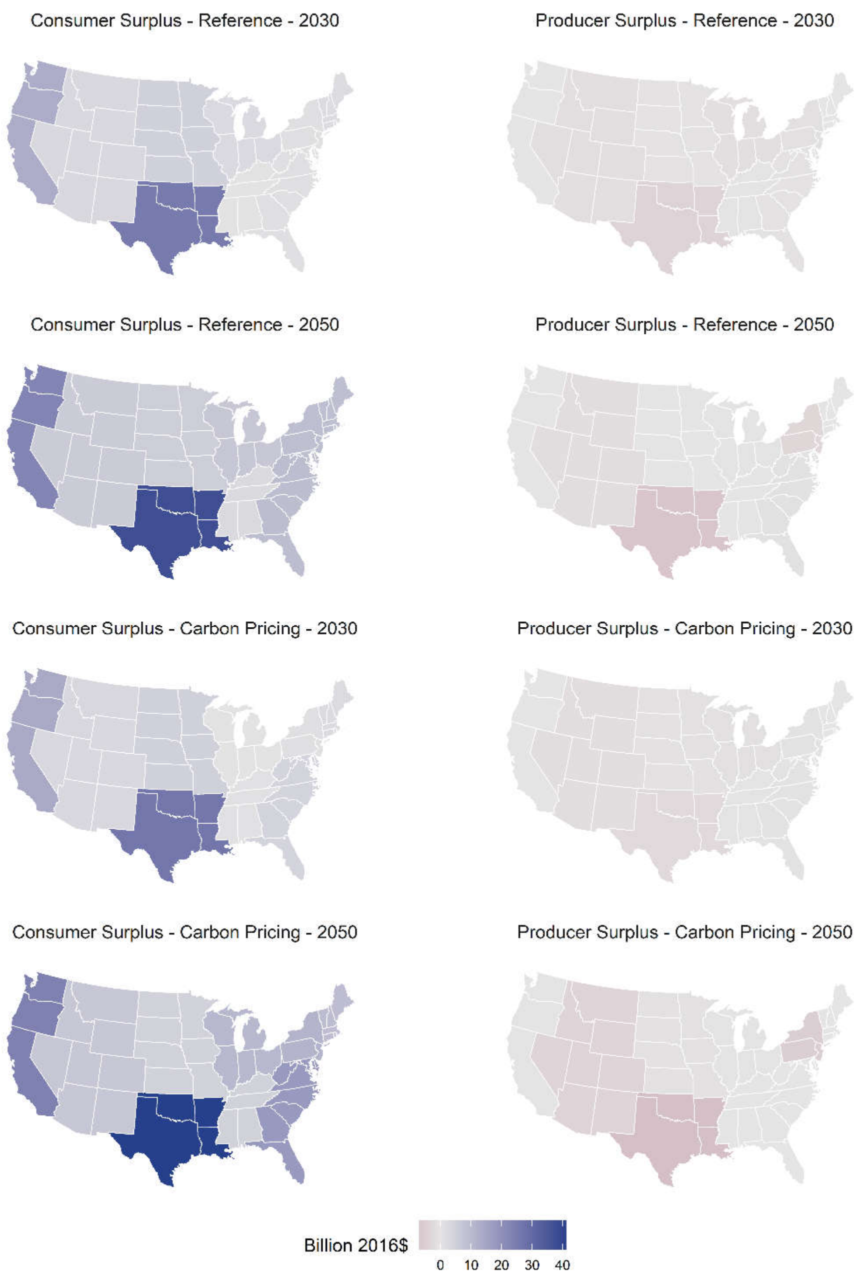

Figure 6: Change in consumer and producer surplus due to abundant natural gas relative to the reference and carbon pricing scenarios in 2030 and 2050

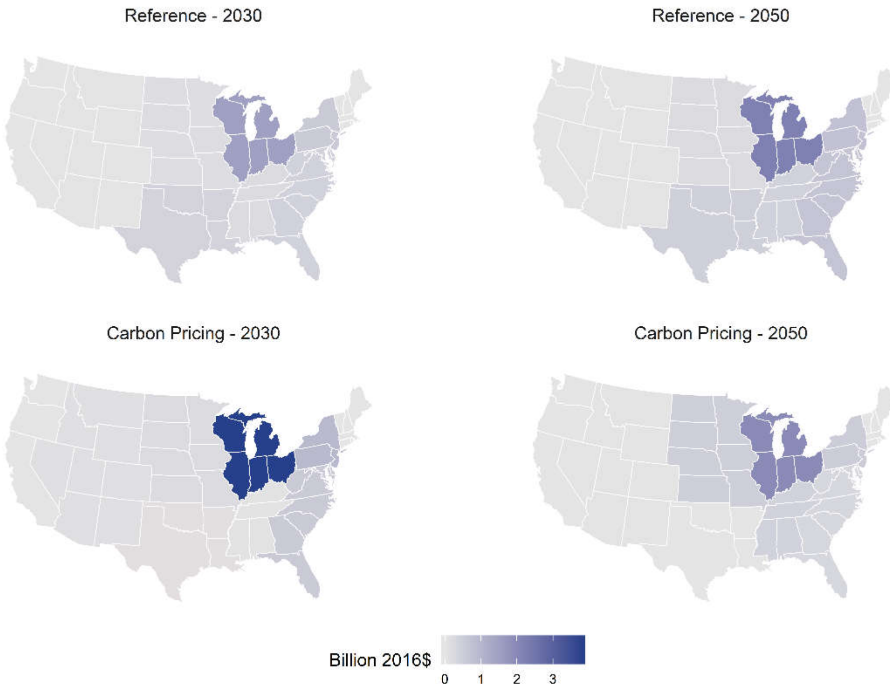

Figure 7: Benefits from reduced monetized pollutant damages from the abudant natural gas scenario relative to the reference and carbon pricing cases in 2030 and 2050

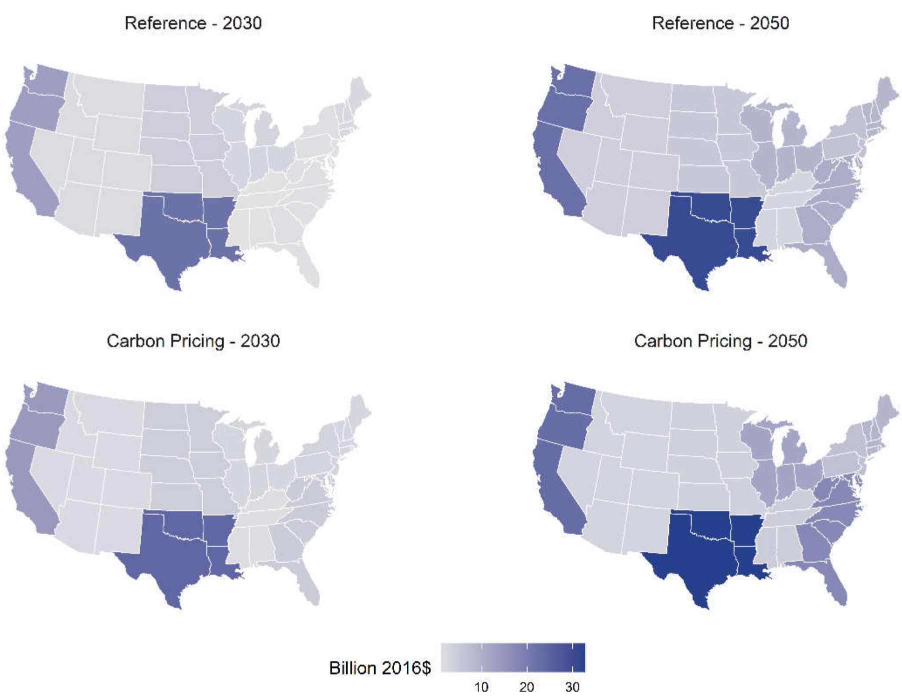

Figure 8: Change in total welfare from abundant natural gas supply when compared to the reference and carbon pricing cases in 2030 and 2050

Table 1: Projected U.S. natural gas production

Year	Reference	Abundant Gas	Carbon Pricing	Abundant Gas & Carbon Pricing
2017	27.86	27.91	27.86	27.91
2020	30.82	32.63	30.85	32.90
2025	32.89	36.91	33.12	38.02
2030	34.24	39.56	34.98	41.53
2035	36.00	42.19	36.95	44.69
2040	37.45	44.55	38.83	46.59
2045	38.45	46.52	39.57	47.80
2050	39.72	48.56	40.14	48.80

Notes: the unit is Tcf.

Table 2: National summary of change in welfare in 2030 and 2050

	Abundant Gas vs. Reference		Abundant Gas & Carbon Pricing vs. Carbon Pricing		Carbon Pricing vs. Reference		Abundant Gas & Carbon Pricing vs. Reference	
	2030	2050	2030	2050	2030	2050	2030	2050
Change in consumer surplus	53.11	106.90	55.33	128.87	-98.78	-247.64	-46.86	-125.24
Change in producer surplus	-9.01	-10.77	-5.84	-17.19	-2.46	-5.24	-8.30	-22.43
Monetized benefits from reducing CO_2	1.94	-0.96	4.13	-3.13	148.80	292.30	152.93	289.17
Monetized benefits from reducing other pollutants	3.18	4.74	5.49	3.68	7.57	15.19	13.05	18.87
Total	49.23	99.91	59.10	112.22	55.12	54.61	110.81	160.36

Notes: the unit is billion 2016$.