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Can deployment of renewable energy put downward pressure on natural gas prices?

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Abstract

High and volatile natural gas prices have increasingly led to calls for investments in renewable energy. One line of argument is that deployment of these resources may lead to reductions in the demand for and price of natural gas. Many recent US-based modeling studies have demonstrated that this effect could provide significant consumer savings. In this article we evaluate these studies, and benchmark their findings against economic theory, other modeling results, and a limited empirical literature. We find that many uncertainties remain regarding the absolute magnitude of this effect, and that the reduction in natural gas prices may not represent an increase in aggregate economic wealth. Nonetheless, we conclude that many of the studies of the impact of renewable energy on natural gas prices appear to have represented this effect within reason, given current knowledge. These studies specifically suggest that a 1% reduction in US natural gas demand could lead to long-term average wellhead price reductions of 0.8–2%, and that each megawatt-hour of renewable energy may benefit natural gas consumers to the tune of at least $7.5–20.

Keywords: Renewable energy; Natural gas prices; Risk mitigation

1. Introduction

Renewable energy has historically been supported because of its perceived economic, environmental, economic-development, and national-security benefits. Recently, extreme price volatility in wholesale electricity and natural gas markets has led to discussions about the potential risk mitigation value of renewable resources in the United States and elsewhere. Deepening concerns about the ability of conventional gas production to keep up with demand have also resulted in a growing number of voices calling for resource diversification (see, e.g., Bernstein et al., 2002; Henning et al., 2003; NARUC, 2003; NPC, 2003a).

Renewable energy provides a direct hedge against volatile and escalating gas prices when it reduces the need to purchase variable-price natural gas-fired electricity generation, replacing that generation with fixed-price renewable energy (see, e.g., Bolinger et al., 2003; Awerbuch, 2003). In addition to this *direct* contribution to price stability, by displacing gas-fired generation, renewable energy may also reduce demand for natural gas and thus *indirectly* place downward pressure on gas prices.

Many recent modeling studies of increased renewables deployment in the United States have demonstrated that this "secondary" effect of putting downward pressure on natural gas prices could be significant, with the consumer benefits from reduced gas prices in many cases more than offsetting any increase in electricity costs caused by renewables deployment. As a result, this price effect is increasingly cited as justification for policies promoting renewable energy.[1]

To date, little work has focused on reviewing the reasonableness of this price-suppression effect as it is portrayed in various studies, and research has not attempted to benchmark the modeling results against economic theory. This article is a first attempt to address these two issues. Although we emphasize the impact of renewable energy on natural gas prices, we acknowledge

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[1]These effects may not appear to be present in analyses of carbon reduction policies more generally, however, because such policies are likely to lead to a shift from coal- to gas-fired generation.

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that similar effects would result from greater energy efficiency, as well as increased utilization of other non-gas energy sources whose fuel costs are not highly correlated with the price of natural gas (e.g., coal or nuclear power, but not oil-fired generation). Additionally, while our analysis focuses on the US, similar effects might be expected elsewhere.

The remainder of this article is organized as follows. Section 2 reviews economic theory to explain the principles underlying the price-suppression effect. Section 3 examines many of the modeling studies conducted during the past 5 years that have measured the price-reduction effect, illustrating the potential impacts of renewables deployment on natural gas demand and wellhead prices, as well as on consumer electricity and gas bills. Section 4 calculates the long-term inverse price elasticity of natural gas supply implied by the modeling output of each of the studies, allowing us to assess the consistency of the natural gas price response among the modeling results. Section 5 compares the range of inverse price elasticities from Section 4 with results from other analyses using the Energy Information Administration's (EIA)'s National Energy Modeling System (NEMS) (to test for intra-model consistency) and with other energy models altogether (to test for inter-model consistency). Section 6 compares the inverse price elasticities from Section 4 with the limited empirical economics literature that estimates the historical elasticities for natural gas and other energy commodities (to test for model consistency with the real world). In Section 7 we summarize our key findings.

2. Natural gas supply and demand: a cursory review of economic theory

The subsections below review the economic concepts of supply and demand curves as they relate to natural gas, introduce the inverse price elasticity of natural gas supply, and discuss the nature of the benefit derived from a reduction in natural gas demand and prices.

2.1. Supply and demand curves

It is not clear whether today's inflated natural gas prices represent a short-term imbalance between supply and demand or a longer-term effect that reflects the true marginal cost of production (see, e.g., EMF, 2003; Henning et al., 2003; Holtberg, 2002; NPC, 2003a). In either case, however, economic theory predicts that a reduction in natural gas demand caused by increased deployment of renewable energy will—by causing an inward shift in the aggregate demand curve for natural gas—generally lead to a reduction in the price of natural gas relative to the price that would have been expected under business-as-usual conditions.[2] The magnitude of the price reduction will depend on the amount of demand reduction, with greater displacement of demand for gas leading to greater drops in the price of the commodity.[3] Equally important, the shape of the natural gas supply curve will have a sizable impact on the magnitude of the price reduction.

The shape of the supply curve for natural gas will, in turn, depend on whether one considers short- or long-term effects. One generally assumes upward, steeply sloping supply curves in the short term when supply constraints exist in the form of fixed inputs like labor, machinery, and well capacity (Henning et al., 2003). In the long term, the supply curve will presumably flatten because supply will have time to adjust to higher (or lower) demand expectations, for example, through increased (or decreased) exploration and drilling expenditures (Dahl and Duggan, 1998). Because natural gas is a non-renewable commodity, however, the long-term supply curve must eventually slope upward as the least-expensive resources are exhausted.

The shape of the long-term supply curve is an empirical question and is subject to great uncertainty and debate. Nonetheless, economists generally agree that the long-term supply curve will generally be flatter than the short-term supply curve. This implies that the impact of increased renewable energy deployment on natural gas prices, on a per-MWh basis, will be greater in the short term than in the long term.[4]

In this article, we primarily emphasize the long-term impacts of renewable energy investments in the US as a whole, and thus focus most of our attention on the shape of the long-term supply curve, ignoring gas transportation constraints. We take this approach for two key reasons. First, renewable energy investments are typically long term in nature, so their most enduring effects are likely to occur over the long term. Second, the model results presented in this paper often do not clearly distinguish between short- and long-term effects, but appear to focus on long-term, national-level impacts.

2.2. Measuring the inverse price elasticity of supply

It is convenient to use elasticity measures to estimate the degree to which shifts in natural gas demand affect the

[2]It is worthy of note that natural gas prices may fall over time even with increasing demand if technological progress allows gas to be extracted at lower prices despite the need to extract resources from increasingly less attractive resource areas. Our argument here is simply that a reduction in natural gas demand is expected, *all else being equal*, to result in lower natural gas prices than would be seen under a higher-demand scenario.

[3]We would not generally expect any particular threshold of demand reduction to be required to lower the price of gas (unless the supply curve was flat over some of its range). Instead, greater quantities of gas savings should result in higher levels of price reduction. The impact on prices, however, need not be linear over the full range of demand reductions; it will, instead, depend on the exact—as yet unknown—shape of the supply curve in the region in which it intersects the demand curve.

[4]Note that the long-term *demand* curve is also expected to be flatter than the short-term *demand* curve (EMF, 2003). This too will moderate the long-term impacts of renewable energy investments on natural gas prices.

price of natural gas, and we use such measures in later sections of this article. The *price elasticity of natural gas supply* is a measure of the responsiveness of natural gas supply to changes in the price of the commodity at a specific point on the supply curve, and is calculated by dividing the percentage change in quantity supplied by the percentage change in price:

$$E = (\%\Delta Q)/(\%\Delta P), \quad (1)$$

where Q and P denote quantity and price, respectively.

In the case of induced shifts in the demand for natural gas, however, we are interested in understanding the change in price that will result from a given change in quantity, or the *inverse price elasticity of supply* (inverse elasticity):

$$E^{-1} = (\%\Delta P)/(\%\Delta Q). \quad (2)$$

For example, an inverse elasticity of 2.2 would mean that a 1% reduction in demand should lead to a 2.2% reduction in price. Given greater supply responsiveness over the long term than in the short term, the long-term supply curve should exhibit *lower* inverse price elasticities of supply than will the short-term supply curve.

2.3. Social benefits, consumer benefits, and wealth transfers

We have made the case that increased deployment of renewable energy can and should lower the price of natural gas relative to a business-as-usual trajectory. This price reduction will benefit consumers by reducing the price of gas delivered to electricity generators (assumed to be passed through in the form of lower electricity prices), and by reducing the price of gas delivered for direct use in the residential, commercial, industrial, and transportation sectors. Before proceeding, however, it is important to address the exact nature of this "benefit," because mischaracterizations are common and may lead to unrealistic expectations and policy prescriptions.

In particular, according to economic theory, lower natural gas prices that result from an inward shift in the demand curve do not necessarily lead to a net gain in economic welfare, but may instead represent a shift of resources (i.e., a transfer payment) from natural gas producers to natural gas consumers. As natural gas producers see their profit margins decline (a loss of producer surplus), natural gas consumers benefit through lower gas bills (a gain of consumer surplus). *Assuming a perfectly competitive and well-functioning aggregate economy*, the net effect on aggregate worldwide social welfare (producer plus consumer surplus) is zero. Wealth transfers of this type are not a standard, primary justification for policy intervention on economic grounds.

Reducing gas prices may still be of importance in policy circles, however, where it may be viewed as a positive ancillary effect of renewable energy deployment. Energy programs are frequently assessed using consumer impacts as a key metric. Furthermore, the wealth redistribution effect may, in fact, result in a social welfare gain if economy-wide macroeconomic adjustment costs are expected to be severe in the case of natural gas price spikes and escalation. Such adjustment costs have been found to be significant in the case of oil price shocks and one might expect to discover a similar effect for natural gas, though research has not yet targeted this issue.[5] Awerbuch and Sauter (2005) have additionally argued that lower gas prices may result in reductions in oil demand and oil prices, indirectly reducing the macroeconomic costs of oil price shocks. Moreover, if producers are located outside of the country in question—an increasingly likely situation in the US as the country becomes more reliant on imports of natural gas [especially liquefied natural gas (LNG)]—the wealth redistribution would increase aggregate domestic welfare.[6] Finally, lower natural gas prices may help preserve domestic manufacturing jobs, lead to displacement of more-polluting energy sources, and reduce the cost of environmental regulatory compliance. Given these considerations, we believe that a case can be made for considering the gas-price effects of increased renewable energy supply in policy evaluation, though we leave it to others to further debate this point.

3. Review of previous studies

A number of recent studies have estimated the impact of increased deployment of renewable energy on natural gas prices in the US. Many of these studies have evaluated a *renewables portfolio standard* (RPS)—a policy that requires electricity suppliers to source an increasing percentage of their supply from renewable energy over time; other studies have looked at renewable energy deployment in combination with energy efficiency and environmental policies. In most cases, national-level policies have been the focus of attention, but state- or regional-level policies have also been evaluated.

We compiled and evaluated information from 13 such studies: (1) five studies by the EIA focusing on US national RPS policies, two of which model multiple RPS scenarios; (2) six studies of national RPS policies by the Union of Concerned Scientists (UCS), three of which model multiple RPS scenarios, and one of which also includes aggressive energy efficiency investments; (3) one study by the Tellus Institute that evaluates three different standards of a state-level RPS in Rhode Island (combined with RPS policies in Massachusetts and Connecticut); and (4) an American Council for an Energy-Efficient Economy (ACEEE) study

[5]Although the literature on the macroeconomic impacts of oil-price escalation is broad, we are not aware of research that has explored the impact of natural gas price escalation. Extrapolating from studies that have looked at oil-price shocks, Brown (2003) estimates that a sustained doubling of natural gas prices might reduce US gross domestic product by 0.6–2.1% below what it otherwise would be.

[6]See Parry and Darmstadter (2003) for a recent summary of the literature on the costs of oil dependency, including macroeconomic adjustment costs and inter-country transfers.

that explores the impact of national and regional renewable energy and energy efficiency deployment on natural gas prices.[7] All relevant US-based studies for which we were able to obtain comprehensive data were included.

The energy models used for these studies do not exogenously define a simple, transparent, long-term natural gas supply curve; instead, a variety of modeling assumptions and inputs are made that, when combined, implicitly define the long-term supply curve. For this reason, we must evaluate the long-term gas price effect of renewable energy by measuring the inverse price elasticity of supply in an implicit fashion—i.e., by reviewing modeling results.

The vast majority of the studies reviewed here rely on the NEMS, which is a national energy model developed and operated by the US Department of Energy's (DOE) EIA. The EIA, UCS, and Tellus studies were all conducted using this model. However, because NEMS is revised annually and these studies were conducted during different years, they used different versions of NEMS. In addition, some of the studies summarized in this article used modified versions of NEMS with, for example, different renewable energy potential and cost assumptions. The ACEEE study used an energy model from Energy and Environmental Analysis (EEA) and, unlike the other studies, focused on the *shorter-term* impacts of renewable energy and energy efficiency investments in easing gas prices. As such, results from the ACEEE study are not entirely comparable to those reported for the other studies.

Though most of the results presented in this paper therefore derive from a single energy model (NEMS), biasing the results somewhat, we benchmark these results against other commonly used energy models (Section 5) and against a historical literature that reviews the supply elasticity of energy commodities (Section 6). These comparisons allow greater confidence in our results.

The subsections below review the aggregate, US national results from these studies: specifically national gas-consumption and price impacts, national electricity- and gas-bill impacts, and the dollar per megawatt-hour (MWh) value of renewable energy investments.

3.1. National gas-consumption and price impacts

Table 1 summarizes some of the key results of these studies.[8] As shown, some of the studies predict that increased renewable energy generation (and energy efficiency, if applicable) will modestly increase retail electricity prices on a national average basis, though more recent studies have sometimes found small price reductions (due to improved renewable energy economics relative to gas-fired generation). Increased renewable energy (and energy efficiency in the two studies that include it) also causes a reduction in US natural gas consumption, ranging from less than 1% to nearly 30% depending on the study. This reduced gas consumption suppresses natural gas prices, with price reductions ranging from virtually no change in the US average wellhead price to a 50% reduction in that price.[9] A national effort to serve 10% of US electricity supply with non-hydro renewable sources is found to reduce average wellhead gas prices by *as much as* 10%.

These wellhead price reductions translate into lower gas bills for natural gas consumers and, by reducing the price of gas delivered to the electricity sector, moderate the expected renewable energy-induced increase in electricity prices predicted by many of the studies. Though not shown here, Wiser et al. (2005) demonstrate that the absolute reduction in delivered natural gas prices for the electricity and non-electricity sectors largely mirrors the reduction in wellhead gas prices shown in Table 1. This suggests that changes in wellhead prices flow through to delivered prices for all US consumers—even those consumers located in regions that do not experience significant renewable energy development—on an approximate one-for-one basis.

Focusing on those studies that *exclude* energy efficiency deployment (i.e., all but ACEEE, 2003 and UCS, 2001), Fig. 1 graphically presents the impact of increased renewable energy generation on the displacement of US gas consumption in 2020 (relative to the "base-case" forecast). Fig. 2 shows the impact of increased renewable energy generation on the US average wellhead price of natural gas. As shown, increased levels of renewable energy deployment generally lead to higher levels of gas displacement and greater price reductions.

The gas displacement shown in Fig. 1 is affected by the amount of renewable energy added to the system (as shown in the figure), and the degree to which that renewable generation offsets gas-fired electric production. Although not shown explicitly here, renewable energy is generally expected to lead to greater reductions in gas consumption (and, therefore, prices) in the studies that rely on lower gas-price forecasts in the business-as-usual scenario. More recent studies, which often rely on higher gas-price forecasts (e.g., UCS, 2004a, b), generally find less gas

[7]In some instances, the studies included in our analysis actually incorporated multiple sensitivity cases in addition to different RPS standard levels (e.g., different cost caps or policy sunset provisions). In these instances, we selected just one of the sensitivity cases to report here.

[8]Table 1 presents the projected impacts of increased renewable energy (and energy efficiency, where applicable) deployment in each study relative to some baseline. The baselines differ from study to study, which partially explains why, for example, a 10% RPS in two studies can lead to different impacts on renewable generation (in TWh and in percentage increase in renewable generation, above the baseline). The impact on renewable generation also varies because of assumed cost caps used in some studies or sunset provisions that in some studies terminate the RPS in a certain year, leading to fewer modeled renewable capacity additions in later years

(*footnote continued*)
of the study because there are fewer years under the RPS in which to recoup investment costs. Additional variations among model runs include renewable technology and cost assumptions and the treatment of the federal production tax credit for wind power.

[9]Note that the models capture the secondary or "rebound" effect of reduced prices on natural gas consumption (i.e., lower prices cause demand to rebound somewhat). The modeling results presented here represent projected impacts after such secondary effects have taken place.

Table 1
Summary of results from past renewable energy deployment studies

Author	RPS/EE	Increase in US renewables TWh (% of total generation)	Reduction in US gas consumption Quads (%)	Gas wellhead price reduction \$/MMBtu (%)	Retail electric price increase Cents/kWh (%)
EIA (1998)	10%—2010 (US)	336 (6.7%)	1.12 (3.4%)	0.34 (12.9%)	0.21 (3.6%)
EIA (1999)	7.5%—2020 (US)	186 (3.7%)	0.41 (1.3%)	0.19 (6.6%)	0.10 (1.7%)
EIA (2001)	10%—2020 (US)	335 (6.7%)	1.45 (4.0%)	0.27 (8.4%)	0.01 (0.2%)
EIA (2001)	20%—2020 (US)	800 (16.0%)	3.89 (10.8%)	0.56 (17.4%)	0.27 (4.3%)
EIA (2002a)	10%—2020 (US)	256 (5.1%)	0.72 (2.1%)	0.12 (3.7%)	0.09 (1.4%)
EIA (2002a)	20%—2020 (US)	372 (7.4%)	1.32 (3.8%)	0.22 (6.7%)	0.19 (2.9%)
EIA (2003)	10%—2020 (US)	135 (2.7%)	0.48 (1.4%)	0.00 (0.0%)	0.04 (0.6%)
UCS (2001)	20%—2020, & EE (US)	353 (7.0%)	10.54 (29.7%)	1.58 (50.8%)	0.17 (2.8%)
UCS (2002a)	10%—2020 (US)	355 (7.1%)	1.28 (3.6%)	0.32 (10.4%)	−0.18 (−2.9%)
UCS (2002a)	20%—2020 (US)	836 (16.7%)	3.21 (9.0%)	0.55 (17.9%)	0.19 (3.0%)
UCS (2002b)	10%—2020 (US)	165 (3.3%)	0.72 (2.1%)	0.05 (1.5%)	−0.07 (−1.1%)
UCS (2003)	10%—2020 (US)	185 (3.7%)	0.10 (0.3%)	0.14 (3.2%)	−0.14 (−2.0%)
UCS (2004a)	10%—2020 (US)	181 (3.6%)	0.49 (1.6%)	0.12 (3.1%)	−0.12 (−1.8%)
UCS (2004a)	20%—2020 (US)	653 (13.0%)	1.80 (5.8%)	0.07 (1.87%)	0.09 (1.3%)
UCS (2004b)	10%—2020 (US)	277 (5.5%)	0.62 (2.0%)	0.11 (2.6%)	−0.16 (−2.4%)
UCS (2004b)	20%—2010 (US)	647 (12.9%)	1.45 (4.7%)	0.27 (6.7%)	−0.19 (−2.9%)
Tellus (2002)	10%—2020 (RI)	31 (0.6%)	0.13 (0.4%)	0.00 (0.0%)	0.02 (0.1%)
Tellus (2002)	15%—2020 (RI)	89 (1.8%)	0.23 (0.7%)	0.01 (0.4%)	−0.05 (−0.3%)
Tellus (2002)	20%—2020 (RI)	98 (2.0%)	0.28 (0.8%)	0.02 (0.8%)	−0.07 (−0.4%)
ACEEE (2003)	6.3%—2008, & EE (US)	NA	1.37 (5.4%)	0.74 (22.1%)	NA

EE = energy efficiency.
The data for the ACEEE study are for 2008, the final year of that study's forecast. All other data are for 2020.
All dollar figures are in constant 2000\$.
The increase in US renewables generation reflects the TWh and percentage increase *relative* to the reference case scenario for the year 2020. The percentage figures do not equate to the size of the RPS for a variety of reasons: (1) existing renewables generation and new renewables generation that comes on line in the reference case may also be eligible for the RPS, and (2) the RPS is not always achieved, given assumed cost caps in some studies.
The reference case in most studies reflects an EIA Annual Energy Outlook (AEO) reference case, with some studies making adjustments based on more recent gas prices or altered renewable-technology assumptions. The one exception is UCS (2003), in which the reference case reflects a substantially higher gas-price environment than the relevant AEO reference case.
The Tellus study models an RPS for Rhode Island, also including the impacts of the Massachusetts and Connecticut RPS policies. All the figures shown in this table for the Tellus study, as well as ACEEE (2003), are for the predicted national-level impacts of the regional policies that were evaluated.

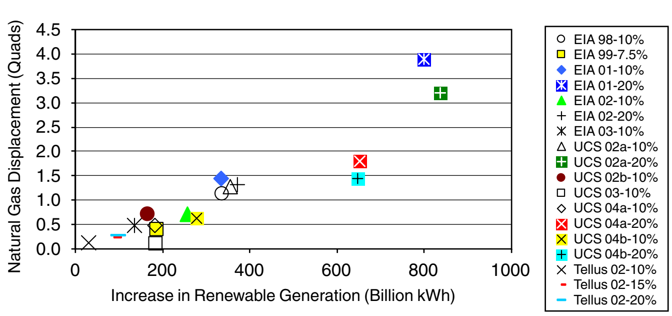

Fig. 1. Forecasted natural gas displacement in 2020.

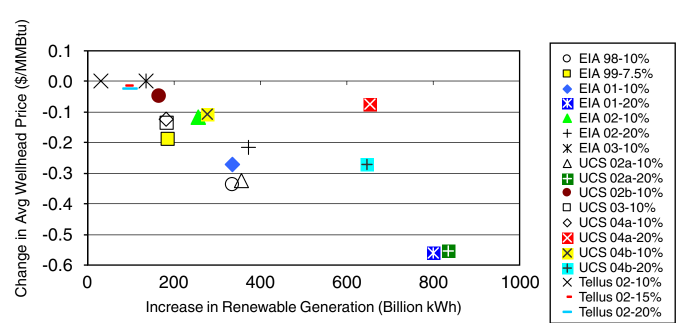

Fig. 2. Forecasted natural gas wellhead price reduction in 2020.

displacement (and greater coal displacement) over time as coal out-competes gas for new generating capacity additions; this effect can be seen in the relatively lower gas displacement and price reduction under the 20% RPS in UCS (2004a) and UCS (2004b).

This effect is shown graphically in Wiser et al. (2005), which finds that the newest studies of US RPS policies—all of which feature higher base-case gas price forecasts—show that each MWh of renewable energy displaces as little as 0.34 MWh of natural gas generation on average, as compared to some earlier studies featuring lower gas price forecasts that show an average displacement of more than 0.75 MWh. In a high-gas-price environment, this effect may mitigate the benefit of renewable energy in reducing gas prices. Although it is possible that increased renewable

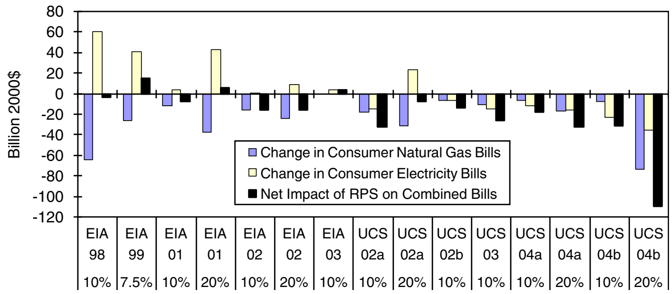

Fig. 3. Present value of RPS impacts on natural gas and electricity bills (2003–2020, 7% real discount rate).

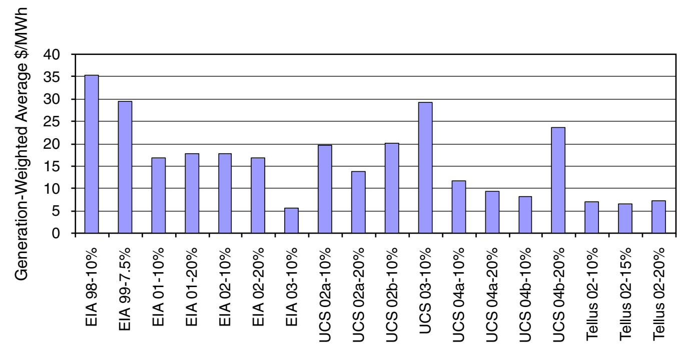

Fig. 4. Consumer gas-savings benefits of increased renewable energy production (in $/MWh).

energy may also put downward pressure on coal prices, the elasticity of coal prices to altered demand conditions is likely to be far lower than that of natural gas (see, for example, Fig. 7 later in this article), suggesting that the impact of renewable energy on coal prices is probably modest relative to its impact on gas prices.

3.2. US national electricity- and gas-bill impacts

The previously presented results show that increased renewable energy is predicted to reduce natural gas consumption and prices while retail electricity prices are predicted to rise in at least some instances. The net predicted effect on US consumer energy bills could be positive or negative, depending on the relative magnitude of the electricity- and natural gas-bill changes.

Fig. 3 presents these offsetting effects for a subset of the studies we reviewed.[10] Although there are variations among the different studies, the present value of the cumulative (2003–2020) predicted increase in consumer electricity bills (if any) in the RPS cases compared to the reference case is often on the same order of magnitude as the present value of the predicted decrease in consumer natural gas bills. From an aggregate *consumer* perspective, therefore, the net consumer cost of these policies is typically predicted to be rather small, with 12 of 15 RPS analyses even showing net consumer savings (i.e., negative cumulative bill impacts).[11]

3.3. The value of renewable energy, in $/MWh

By putting downward pressure on natural gas prices and bills, increased renewable energy seemingly provides a significant benefit to consumers, based on the studies reviewed here. But how large is that US national impact, in dollars per MWh of renewable energy?

Considering the predicted reduction in consumer gas bills as well as an assumed one-for-one pass-through to consumers of gas cost reductions in the electricity sector, Fig. 4 shows the range of consumer benefits delivered by increased renewable energy, by study (not including those studies that also include energy efficiency investments), expressed in terms of $ per MWh of renewable energy.[12]

Results from these studies suggest that each MWh of renewable energy provides, in aggregate, US consumer gas savings benefits in the range of $6–35/MWh, with most studies showing a range of $7.50–20/MWh. Variations in this value are caused by different implied inverse price elasticities of natural gas supply, and by differences in the amount of gas displacement caused by renewable energy. Even at the low end of the range, however, these consumer benefits are sizable.

4. Summary of implied inverse price elasticities of supply

The natural gas price response predicted by these studies can be compared by calculating the inverse price elasticity of supply implied by the results of each study, for each forecast year. This calculation requires annual data on the predicted average US wellhead price of natural gas and total gas consumption in the United States for both the business-as-usual scenario and the policy scenario of increased renewable energy deployment.[13]

[10] Fig. 3 shows the energy bill impacts only for the national RPS studies for which these data were available (i.e., it excludes Tellus (2002), as well as the two studies in which energy efficiency was also included).

[11] In several of these studies, RPS cost caps are reached, ensuring that consumers pay a capped price for some number of *proxy* renewable energy credits (and leading to increased electricity prices) while not obtaining the benefits of increased RE generation on natural gas prices. Accordingly, if anything, Fig. 3 underestimates the possible consumer benefits of a well-designed renewable energy program with less-binding cost caps.

[12] We weight the annual gas bill savings per MWh of renewable energy by the amount of yearly renewable energy to derive the weighted average data in Fig. 4. Yearly data are averaged over the following period: from the first year in which incremental renewable energy supply exceeds 10 billion kWh (to eliminate "noise" in the data) to the last year of the forecast period, either 2020 or 2025 (depending on the study).

[13] The specific calculation is:

$$E^{-1} = (\text{Wellhead price}_{\text{business-as-usual}}/\text{Wellhead price}_{\text{policy}} - 1) \\ /(\text{Gas demand}_{\text{business-as-usual}}/\text{Gas demand}_{\text{policy}} - 1).$$

The inverse elasticity calculations presented here use US price and quantity data under the assumption that the current market for natural gas is more regional than worldwide in nature (Henning et al., 2003). Of

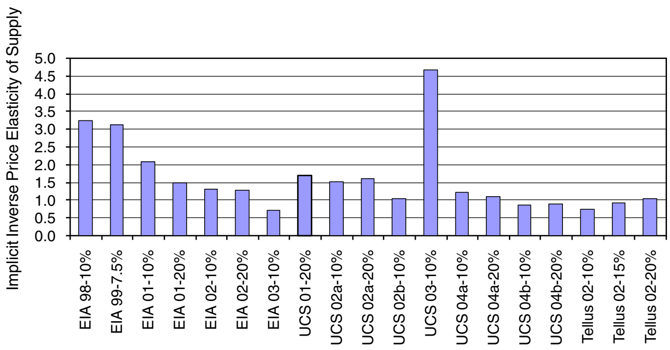

Fig. 5. Average inverse price elasticities of supply.

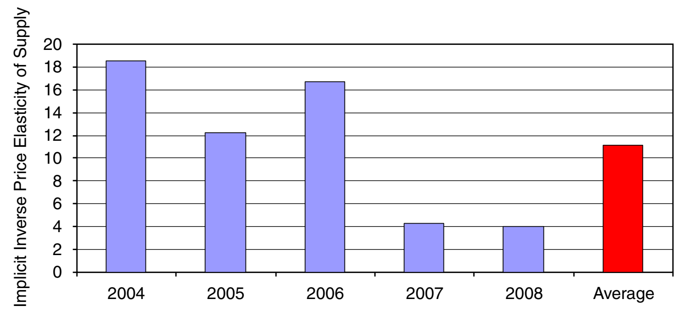

Fig. 6. Implicit inverse price elasticities in ACEEE (2003).

Because relying on the implied inverse elasticity for any *single* year could be misleading, Fig. 5 compares the average value of the *long-term* implicit inverse elasticities among studies (excluding the ACEEE, 2003 results, which are presented later).[14] Despite substantial variations among studies and results for individual years (see Wiser et al., 2005), there is some consistency in the *average* long-term inverse elasticities; the overall range is between 0.7 and 4.7, with elasticites from 13 of 19 analyses (all of which use NEMS) falling between 0.8 and 2.0.[15] This means that each 1% reduction in US natural gas demand is expected to lead to a 0.8–2% reduction in wellhead gas prices.

Though the implied inverse elasticities derived from NEMS represent the long-term supply curve for natural gas, this may not be the case in the ACEEE study. The ACEEE study reports the impact of increased renewable energy and energy efficiency deployment over a shorter period (2004–2008) than the other studies and uses a gas-market model from EEA that reports impacts on a more disaggregated basis by region and by time interval than NEMS, considering regional transportation and supply constraints.

Although the ACEEE study analyzed the potential impact of both state and regional renewable energy and energy efficiency deployment, Fig. 6 only reports the results of the national US deployment scenario. This figure shows that ACEEE's implied inverse elasticities are high, at more than 10 in the early years; by 2008, the inverse elasticity drops to four, which is still more than twice as high as the average long-term inverse elasticity implicit in the latest versions of NEMS (though it is consistent with other recent long-term analyses conducted with the EEA model).[16]

Because the other studies reviewed in this article do not seek to present short-term impacts at the same level of disaggregation as ACEEE, it is difficult to compare the ACEEE results with those of other studies. The short-term impacts forecast by ACEEE are aggressive, however, and at the least should not be extrapolated to later years. In fact, a recent paper by Costello et al. (2005) argues that recent applications of the EEA model by the National Petroleum Council (NPC) (and, by extension, by ACEEE) show too little demand and supply response to changes in natural gas prices, leading to a demand-induced price response that is higher than would otherwise be expected. By the same token, the ACEEE results suggest that the positive consumer impacts of increased renewable energy (and energy efficiency) may be more significant in the short run than is estimated by other modeling studies whose approaches are arguably better able to address longer-term influences.

5. Benchmarking against other analyses and energy models

In evaluating the reasonableness of the above results, it is useful to compare the inverse elasticities implied by the renewable energy deployment studies to those calculated for natural gas and other fossil fuels in other EIA NEMS analyses as well as those from other national energy models.

In particular, the studies reviewed above address only one type of exogenous demand shock that triggers a natural gas price response. The low- and high-economic

(*footnote continued*)
course, the market for natural gas consumed in the US is arguably a North American market, including Canada and Mexico, with LNG expected to play an increasing role in the future. Trade with Mexico is relatively small, however, and Canadian demand for gas is relatively small compared to US demand. LNG, meanwhile, remains a modest contributor to total US consumption.

[14]Average inverse elasticities are calculated as the average of each year's inverse elasticity, from the first year in which incremental renewable energy production exceeds 10 billion kWh (so that we ignore early year "noise" in the data) to the last year of the forecast period, 2020 or 2025, depending on the study.

[15]The average inverse elasticity from UCS (2003) is substantially higher than that from most of the other studies. As noted earlier, UCS (2003) evaluated the potential impact of an RPS under a scenario of higher gas prices than in a typical AEO reference case, so that study is not strictly comparable to the others covered in this paper (specifically, the UCS study includes a more constrained gas supply than most of the other analyses, especially in the later years, and so is likely measuring changes along a steeper portion of the supply curve).

[16]The natural gas price data used to construct the inverse elasticities implicit in the ACEEE results are projected Henry Hub prices; the previously mentioned studies relied on wellhead price projections. Because Henry Hub prices are typically higher than wellhead prices, inverse elasticities calculated with Henry Hub data will be somewhat lower than would be the case if wellhead prices were used.

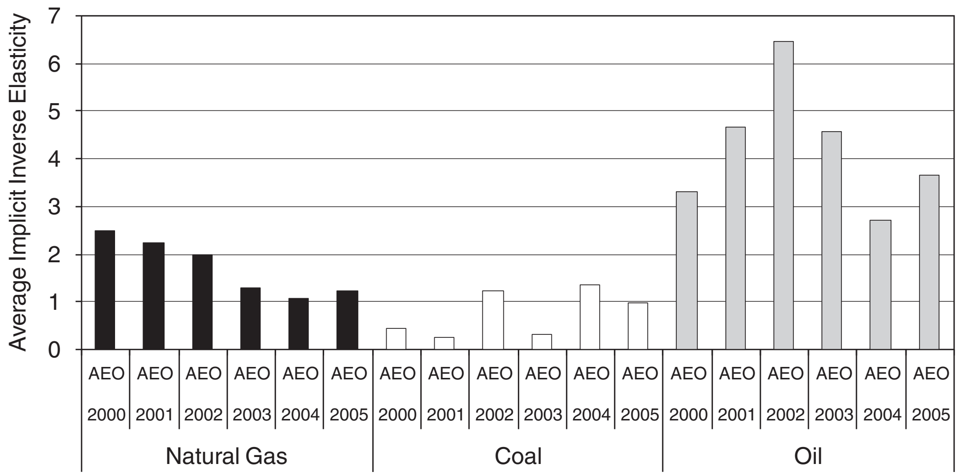

Fig. 7. Average implicit inverse price elasticities for gas, coal, and oil under the AEO's low-economic-growth case.

growth scenarios published as part of the EIA's Annual Energy Outlook (AEO) each year are another such example. Low economic growth, compared to the reference case, leads to less demand for fossil fuels, and high economic growth results in the opposite effect. Fig. 7 shows the range of average (2003–2020) implied inverse elasticities for natural gas, coal, and oil from AEO 2000–2005, focusing on the low-economic-growth case relative to the reference-case forecast.[17]

The average implicit inverse elasticities for natural gas shown in Fig. 7 are broadly consistent with the results of the NEMS-based renewable energy deployment studies presented earlier, i.e., they range from 1.1 to 2.5, consistent with 14 of 19 of the previously presented analyses. Fig. 7 also shows that the implicit inverse elasticities for gas appear to have decreased somewhat with successive versions of NEMS, which the EIA updates each year.[18] As might be expected given plentiful and relatively inexpensive domestic coal supplies, the implicit inverse elasticity for coal is generally lower than that for gas and oil. The inverse elasticity for oil, on the other hand, is *much* higher than those for coal and gas, reflecting an assumption of highly inelastic supply.[19]

Finding a degree of consistency between the results of the renewable energy deployment studies presented earlier and the AEO's economic-growth cases presented here is not surprising because, with the exception of the ACEEE study, each of these studies used NEMS. We therefore also sought to compare the long-term inverse elasticites implicit in NEMS with those of other national energy models. Data from a recent study by Stanford's Energy Modeling Forum (EMF, 2003) allow for this comparison. In particular, the EMF study presents the potential impact of high gas demand on US natural gas consumption and price in 2005, 2010, 2015, and 2020, using seven different energy models. Using the price and demand series' provided, Table 2 presents the inverse elasticities that underlie this analysis.[20]

The table shows that inverse elasticity estimates vary substantially among the major national energy models reviewed by the Stanford study. Nonetheless, five of the seven models (NEMS, POEMS, CRA, E2020, and MARKAL) report inverse elasticity estimates that are broadly consistent with those presented earlier. Two of the models (NANGAS and NARG) report somewhat anomalous results. Some of these models (e.g., POEMS and MARKAL) rely in part on modeling inputs to NEMS, however, making consistency among the models perhaps less significant than otherwise would be the case. Moreover, the EMF report does not explain the relatively high inverse elasticities for NANGAS and NARG, or why the

[17]Like the natural gas market, the coal market is assumed to be national, and the implicit inverse elasticity was calculated using forecasts of US coal minemouth prices and total US coal consumption. Oil, on the other hand, is assumed to be a world market, so the elasticity calculation used the world oil price and total world oil consumption from the AEOs.

[18]This may in part result from an assumption of increased imports from outside of the lower-48 states, including substantial increases in the role of imported LNG. Such trade may make natural gas a less-national and more-worldwide market, with prices determined in part by worldwide supply-demand dynamics.

[19]Additional research would need to be conducted to determine whether such a high inverse elasticity is plausible.

[20]The EMF scenarios modeled the impact of *increased* gas demand on price (an outward shift in the demand curve) whereas we are primarily interested in the impact of *decreased* gas demand on price (an inward shift in the demand curve). Assuming a smooth supply curve over the long term, however, the elasticities implied by an increase in demand should be essentially equivalent to those implied by a decrease in demand and thus should be comparable to what is addressed in the renewable energy studies described earlier in this paper. The data presented here primarily derive from an excel spreadsheet available on the EMF website (http://www.stanford.edu/group/EMF/publications/index.htm), which reports the results of the EMF modeling runs. The only exception is that the MARKAL results come from the EMF report itself, because data were not available for MARKAL in the spreadsheet. It should be noted that the data presented in the spreadsheet do not perfectly match the data presented in the formal EMF report; the reason for this discrepancy is not clear.

Table 2
Implicit inverse elasticities in a range of national energy models

Energy model	Implicit inverse price elasticity of supply			
	2005	2010	2015	2020
NEMS	1.8	2.2	0.53	0.11
POEMS	2.4	1.8	2.5	1.8
CRA	3.5	2.5	1.1	0.9
NANGAS	5.4	7.0	7.6	5.1
E2020	1.5	1.0	1.0	0.7
MARKAL	N/A	2.0	N/A	2.1
NARG	8.7	12.4	5.6	2.4

NEMS—National Energy Modeling System; POEMS—Policy Office Electricity Modeling System; CRA—Charles River Associates; NANGAS—North American Natural Gas Analysis System; E2020—Energy 2020; MARKAL—MARKet ALlocation; NARG—North American Regional Gas model.

inverse elasticity for NEMS (and, to a lesser extent, CRA) drops substantially over time.[21]

The NPC, meanwhile, recently issued a study relying on the EEA model. The sensitivity cases in that study show an average implicit long-term inverse elasticity (2011–2025) of approximately four (NPC, 2003b). This value is consistent with the year 2007 and year 2008 ACEEE results presented earlier in Fig. 6, which also relied on the EEA model. Another recent study commissioned by the National Commission on Energy Policy, and using the same EEA model, estimates inverse elasticities that are as high as 16.8 in 2010, dropping to 5.3 in 2020, and then increasing to 7.7 in 2025 (National Commission on Energy Policy, 2003). These findings clearly show that the EEA model predicts higher short-term and long-term inverse elasticities than several of the other commonly used national energy models; as noted earlier, Costello et al. (2005) criticize the recent application of the EEA model in part on this basis.

6. Benchmarking against empirical elasticity estimates

With few exceptions, the energy-modeling results reviewed previously tell a consistent, basic story: reducing the demand for natural gas through the use of renewable energy is expected to lead to lower natural gas prices than would be the case in a business-as-usual scenario. Although the magnitude of the long-term implicit inverse price elasticity of supply varies among models and years, the central tendency appears to be values of 0.8–2. That is, a 1% reduction in US national gas demand is expected to cause a corresponding wellhead price reduction of 0.8–2% in the long-term, with some models predicting even larger effects (4% + reductions in long-term gas prices for each 1% drop in gas consumption).

These are modeling predictions, however, which are based on an estimated shape of a natural gas supply curve that is not known with any precision. It is fair to say that modelers have a dismal track record in accurately estimating future natural gas prices, which raises questions about the degree of confidence we should place in these modeling results. One way to address these questions is to benchmark gas-price forecasts against empirical estimates of historical inverse elasticities. Although empirically derived estimates of historical inverse elasticities will not predict future elasticities accurately (the natural gas supply curve should have a different shape in 2010 than it did in 1990), and data and analysis difficulties plague such estimates, these estimates are nonetheless a dose of empirical reality relative to the modeling results presented earlier.

Unfortunately, empirical research on energy elasticities has focused almost exclusively on the impact of supply shocks on energy *demand* (demand elasticity) rather than the impact of demand shocks on energy *supply* (supply elasticity). Our literature search uncovered only one recently published empirical estimate of the long-term supply elasticity for natural gas. Krichene (2002) estimates this long-term supply elasticity to be 0.8 (for the period 1973–1999), yielding an *inverse* elasticity of 1.25.Surprisingly, this is *larger* than Krichene's short-term inverse elasticity, estimated to be −10.[22] Examining the 1918–1973 time period separately, Krichene estimates inverse elasticities of 3.57 in the long term and −1.36 in the short term. Krichene estimates these elasticities using US wellhead prices and international natural gas production, however, making a direct comparison to the model results presented earlier impossible.[23]

With only one published figure (of which we are aware) for long-term natural gas supply elasticity, it may be helpful to review published estimates for other non-renewable-energy commodities, namely oil and coal. Few supply constraints exist for coal, and long-term inverse elasticities are therefore expected to be lower than for natural gas. Oil production, though clearly a worldwide

[21]We chose not to comprehensively review elasticity estimates provided in earlier models or econometric analyses (see, e.g., Huntington and Schuler, 1990; Pindyck, 1974), under the assumption that more recent comparisons would be most relevant. A review of national energy models by Huntington and Schuler (1990), however, reveals that elasticities implicit in energy models during the late 1980s are consistent with those in the more recent EMF (2003) study. In particular, Huntington and Schuler (1990) report inverse price elasticities of supply (projected for 2000) that range from 1.1 to 3.3 and are clustered around 1.6–2.5.

[22]The negative sign on the short-term inverse price elasticity implies that producers will respond to higher prices by reducing production, the opposite of what economic theory would normally expect. To explain this, Krichene (2002) postulates that natural gas production may experience economies of scale and thus a downward sloping short-term supply curve, or alternatively, that producers may recognize the inelastic nature of demand and deliberately restrain output in order to sustain any surge in prices.

[23]One additional study (reported in Dahl and Duggan, 1996) estimates the short-term inverse elasticity of natural gas to range from 6.7 to 37 (Barret, 1992).

rather than regional market, has more in common with gas, but the Organization of Petroleum Exporting Countries (OPEC) exerts uncompetitive influences on oil-supply behavior. The comparability of natural gas, oil, and coal elasticities is therefore questionable.

Hogan (1989) estimates short- and long-term inverse elasticities for oil in the US of 11.1 and 1.7, respectively. Looking more broadly at the world oil market, Krichene (2002) calculates the long-term inverse elasticity for oil to be 0.91 from 1918 to 1973, and 10 from 1973 to 1999. Ramcharran (2002) finds evidence of an uncompetitive supply market for oil for the period 1973–1997, with a short-term inverse elasticity estimate of −5.9. For non-OPEC nations, meanwhile, he found a more competitive short-term inverse elasticity of 9.4.[24]

The EIA (2002b) found only two studies that sought to estimate the supply elasticity for coal. The first, by Beck et al. (1991), reportedly estimates an inverse elasticity for the Australian coal industry of 2.5 in the short term and 0.53 in the long term. The second study focuses on the Appalachian region of the US (Harvey, 1986) and estimates inverse elasticities of 7.1 in the short term and 3.1 in the long term.[25]

In summary, there are few empirical estimates of supply elasticities against which to benchmark the modeling output described earlier in this paper, and data and analysis problems plague the estimates described above. As important, given changes in the natural gas marketplace, there is no reason to believe that historical elasticity values will be applicable into the future. Nonetheless, empirical estimates of historical long-term inverse elasticities for gas, coal, and oil are positive, and the modeling output presented earlier for the long-term inverse elasticity of natural gas is not wildly out of line with the historical empirical estimates. Still, the range of implicit long-term inverse elasticities of gas presented earlier is broad, and the empirical literature certainly does not help us narrow that range. In addition, although this view is not clearly supported by either the empirical literature or modeling output, there are some who believe that technological progress is likely to keep the long-term supply curve for natural gas relatively flat, implying a large overstatement of the magnitude of the natural gas price reduction effect in the modeling results presented earlier.

[24]A number of additional studies also report short-term supply elasticities for oil (see Dahl and Duggan, 1996).

[25]It may be relevant to report inverse price elasticities for other non-renewable, non-energy commodities. Although we have not systematically researched comprehensive data on these elasticities, Pindyck and Rubinfeld (1995) report a short-term inverse elasticity of four for copper and a long-term inverse elasticity of 0.67, while Fisher et al. (1972) report short- and long-term inverse elasticites of 2.2 and 0.6, respectively, for copper in the US.

7. Conclusions

Concerns about the price and supply of natural gas in the US have grown in recent years, and futures and options markets predict high prices and significant price volatility for the immediate future. Whether we are witnessing the beginning of a major long-term nationwide crisis or a costly but shorter-term supply demand adjustment remains to be seen.

Results presented in this article suggest that resource diversification, in particular increased investments in renewable energy, could help alleviate the threat of high gas prices over the short and long term. By displacing gas-fired generation, increased deployment of renewable energy is expected to reduce natural gas demand and consequently put downward pressure on gas prices. A review of the economics literature shows that this secondary effect is to be expected and can be measured with the inverse price elasticity of natural gas supply. Because of the respective shapes of long- and short-term supply curves, the long-term price response is expected to be less significant than the shorter-term response.

The effect of this natural gas price reduction may not entirely represent an increase in aggregate economic wealth, and may in part reflect a benefit to natural gas consumers that comes at the expense of natural gas producers. Conventional economics does not generally support government intervention for the sole reason of shifting the demand curve for natural gas and thereby reducing gas prices. If policymakers are uniquely concerned about the impact of gas prices on consumers, however, or are concerned about the potentially harmful macroeconomic impacts of higher gas prices or on increasing imports of natural gas, then policies to reduce gas demand may be considered appropriate. It also deserves note that this secondary gas-price-suppression form of risk mitigation is *additional* to the direct risk-reducing benefit of replacing variable-priced natural gas with fixed-price renewable energy.

A large number of modeling studies in the US have recently been conducted that at least implicitly evaluate the price-suppression effect. Though these studies show a relatively broad range of inverse price elasticities of natural gas supply, and many use the same basic model, we also find that many of them exhibit some central tendencies. Benchmarking these results against other modeling output as well as a limited survey of the empirical literature, we conclude that many of the studies of the impact of renewable energy on natural gas prices appear to have represented this effect within reason, given current knowledge.

Nonetheless, there are sometimes significant variations in the implicit inverse elasticities not only among models but also between years within the same modeling run and between runs using the same basic model. Implied inverse elasticities do not always remain within reasonable bounds. Combine this with the fact that the natural gas supply curve is unknown and that the track record of energy modelers predicting future gas prices has not been good, and it is fair to conclude that not much weight should be placed on any *single* modeling result. More effort needs to be placed on accurately estimating the supply curve for natural gas and on validating models' treatment of that curve before any single modeling result could reasonably be relied upon.

In the mean time, in estimating the impact of renewable energy on natural gas prices, we strongly recommend scenario analysis: it would be preferable to consider a range of natural gas elasticity estimates (as well as gas displacement ratios) to bound a range of potential impacts. Relying on the data summarized in this article, we conclude that each 1% reduction in US national natural gas demand could reasonably be expected to result in long-term average US wellhead price reductions of 0.8–2%, with some of the models predicting more aggressive reductions. Reductions in the wellhead price will not only have the effect of reducing wholesale and retail electricity rates but will also reduce residential, commercial, and industrial gas bills, resulting in a consumer value conservatively estimated to be equivalent to $7.5–20 per MWh of increased renewable energy. A national effort to serve 10% of US electricity supply with non-hydro renewable sources is found to reduce average wellhead gas prices by *as much as* 10%. If considered in the policymaking process, values of this magnitude would support significantly more aggressive efforts to deploy renewable energy technologies.

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References

American Council for an Energy-Efficient Economy (ACEEE), 2003. Natural gas price effects of energy efficiency and renewable energy practices and policies. Report Number E032, American Council for an Energy-Efficient Economy, Washington, DC (Authors: Elliot, R., Shipley, A., Nadel, S., Brown, E.).

Awerbuch, S., 2003. Determining the real cost: why renewable power is more cost-competitive than previously believed. Renewable Energy World 6 (2).

Awerbuch, S., Sauter, R., 2005. Exploiting the oil-GDP effect to support renewables deployment. SPRU Working Paper 129, University of Sussex, Brighton, UK.

Barret, C., 1992. US natural gas market: a disequilibrium approach. In: Proceedings of the international Association for Energy Economics 15th International Conference, G65-G69. Tours, France: International Association for Energy Economics.

Beck, T., Jolly, L., Loncar, T., 1991. Supply response in the Australian black coal industry. Australian Board of Agricultural and Resource Economics, Technical Paper 91.1, Australian Government Publishing Service, Canberra, Australia.

Bernstein, M., Holtberg, P., Ortiz, D., 2002. Implications and Policy Options of California's Reliance on Natural Gas. RAND, Santa Monica, CA.

Bolinger, M., Wiser, R., Golove, W., 2003. Accounting for fuel price risk: using forward natural gas prices instead of gas price forecasts to compare renewable to natural gas-fired generation. LBNL-53587. Lawrence Berkeley National Laboratory, Berkeley, CA.

Brown, S., 2003. US natural gas markets in turmoil. Testimony prepared for a hearing on The Scientific Inventory of Oil and Gas Resources on Federal Lands, US House of Representatives, 19 June.

Costello, K., Huntington, H., Wilson, J., 2005. After the natural gas bubble: an economic evaluation of the recent US National Petroleum Council study. The Energy Journal 26 (2), 89–110.

Dahl, C., Duggan, T., 1996. US energy product supply elasticities: a survey and application to the US oil market. Resources and Energy Economics 18, 243–263.

Dahl, C., Duggan, T., 1998. Survey of price elasticities from economic exploration models of US oil and gas supply. Journal of Energy Finance and Development 3 (2), 129–169.

Energy Information Administration (EIA), 1998. Analysis of S. 687, the Electric System Public Benefits Protection Act of 1997. SR/OIAF/98-01. Energy Information Administration, Washington, DC.

Energy Information Administration (EIA), 1999. Annual energy outlook 2000. DOE/EIA-0383 (2000). Energy Information Administration, Washington, DC.

Energy Information Administration (EIA), 2001. Analysis of strategies for reducing multiple emissions from electric power plants: sulfur dioxide, nitrogen oxides, carbon dioxide, and mercury and a renewable portfolio standard. SR/OIAF/2001-03. Energy Information Administration, Washington, DC.

Energy Information Administration (EIA), 2002a. Impacts of a 10-percent renewable portfolio standard. SR/OIAF/2002-03. Energy Information Administration, Washington, DC.

Energy Information Administration (EIA), 2002b. Model documentation coal market module of the national energy modeling system. DOE/EIA-M060. Energy Information Administration, Washington, DC.

Energy Information Administration (EIA), 2003. Analysis of a 10-percent renewable portfolio standard. SR/OIAF/2003-01. Energy Information Administration, Washington, DC.

Energy Modeling Forum (EMF), 2003. Natural gas, fuel diversity and North American energy markets. EMF Report 20, vol. I, Stanford University, Stanford, CA.

Fisher, F., Cootner, P., Maily, M., 1972. An econometric model of the world copper industry. The Bell Journal of Economics and Management Science 3 (2), 568–609.

Harvey, C., 1986. Coal in Appalachia: An Economic Analysis. University Press of Kentucky, Lexington, KY.

Henning, B., Sloan, M., de Leon, M., 2003. Natural Gas and Energy Price Volatility. Energy and Environmental Analysis, Inc., Arlington, VA.

Hogan, W., 1989. World oil price projections: a sensitivity analysis. Prepared pursuant to the Harvard–Japan World Oil Market Study, Energy Environmental Policy Center, John F. Kennedy School of Government. Harvard University.

Holtberg, P., 2002. Can we have a bright natural gas future with near-term uncertainty? The Journal of Energy and Development 26 (2), 283–300.

Huntington, H., Schuler, G., 1990. North American natural gas markets: summary of an energy modeling forum study. The Energy Journal 11 (2), 1–20.

Krichene, N., 2002. World crude oil and natural gas: a demand and supply model. Energy Economics 24, 557–576.

National Association of Regulatory Utility Commissioners (NARUC), 2003. Natural Gas Information "Toolkit". National Association of Regulatory Utility Commissioners, Washington, DC.

National Commission on Energy Policy, 2003. Increasing US Natural Gas Supplies: A Discussion Paper and Recommendations from the National Commission on Energy Policy. National Commission on Energy Policy, Washington, DC.

National Petroleum Council (NPC), 2003a. Balancing Natural Gas Policy—Fueling the Demands of a Growing Economy, vol. I. Summary of Findings and Recommendations. National Petroleum Council, Washington, DC.

National Petroleum Council (NPC), 2003b. Balancing Natural Gas Policy—Fueling the Demands of a Growing Economy, vol. II. Integrated Report. National Petroleum Council, Washington, DC.

Parry, I., Darmstadter, J., 2003. The costs of US oil dependency. Discussion Paper 03-59. Resources for the Future, Washington, DC.

Pindyck, R., 1974. The regulatory implications of three alternative econometric supply models of natural gas. The Bell Journal of Economics and Management Science 5 (2), 633–645.

Pindyck, R., Rubinfeld, D., 1995. Microeconomics. Prentice-Hall Publishers, Englewood Cliffs, NJ.

Ramcharran, H., 2002. Oil production responses to price changes: an empirical application of the competitive model to OPEC and non-OPEC countries. Energy Economics 24, 97–106.

Tellus, 2002. Modeling Analysis: Renewable Portfolio Standards for the Rhode Island GHG Action Plan. Tellus Institute, Boston, MA.

Union of Concerned Scientists (UCS), 2001. Clean Energy Blueprint: A Smarter National Energy Policy for Today and the Future. Union of Concerned Scientists, Cambridge, MA.

Union of Concerned Scientists (UCS), 2002a. Renewing Where We Live, February 2002 ed. Union of Concerned Scientists, Cambridge, MA.

Union of Concerned Scientists (UCS), 2002b. Renewing Where We Live, September 2002 ed. Union of Concerned Scientists, Cambridge, MA.

Union of Concerned Scientists (UCS), 2003. Renewing Where We Live, September 2003 ed. Union of Concerned Scientists, Cambridge, MA.

Union of Concerned Scientists (UCS), 2004a. Renewable Energy Can Help Ease the Natural Gas Crunch. Union of Concerned Scientists, Cambridge, MA.

Union of Concerned Scientists (UCS), 2004b. Renewing America's Economy: A 20 Percent National Renewable Energy Standard Will Create Jobs and Save Consumers Money. Union of Concerned Scientists, Cambridge, MA.

Wiser, R., Bolinger, M., St. Clair, M., 2005. Easing the natural gas crisis: reducing natural gas prices through increased deployment of renewable energy and energy efficiency. LBNL-56756. Lawrence Berkeley National Laboratory, Berkeley, CA.